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Investigation of a loose-webbed paddle surface impulse propulsor.

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Monterey, California

THESIS

INVESTIGATION OF A LOOSE-WEBBED PADDLE
SURFACE IMPULSE PROPULSOR

by

James Michael Hunn

October 1982

Thesis Advisor: J. F. Sladky

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Investigation of a Loose-Webbed Paddle Surface Impulse Propulsor

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

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October 1982

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The purpose of this investigation was twofold. The first goal was to develop an understanding of the flow behavior and interaction with the blades of a paddlewheel type Surface Impulse Propulsion (SIP) system operating over a water surface. The second goal was to experimentally evaluate the effect of interblade webbing and wheel internal pressure on the thrust performance of a webbed SIP system.

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I. INTRODUCTION

The propulsion of amphibious or all terrain vehicles has been a problem since their earliest introduction. One major difficulty stems from the diversity of type and consistency of the surface over which the craft is to travel. It may range from free surface water to sand and muskeg type terrain that is unable to support the static load of the vehicle. Invariably, a thrust generating system optimally designed for one type of terrain exhibits a significantly degraded performance in other environments.

The solution to this dilemma has traditionally been sought in one of two ways. One method is to design an optimal thrusting system for the environment in which the craft will most often operate and accept decreased performance during operation over different surfaces. The second approach is to configure the vehicle with a plurality of propulsion systems, each optimized for a particular terrain. Common examples are amphibious craft fitted with marine propellors for over water operation and low pressure wheels for land locomotion. Neither of these solutions is entirely satisfactory.

With the advent of Surface Effect Vehicles (SEV), and particularly Air Cushion Vehicles (ACV), the propulsion question becomes even more complex. It is the ACV's ability to hover "above" a surface without contact that constitutes its greatest attraction. From the propulsion perspective, however, this non-contact hovering capability is a source of difficulty.

As a result, the only currently available propulsive systems for ACVs are the air propellor and jet thrust. The technology is derived from aircraft practice. One example

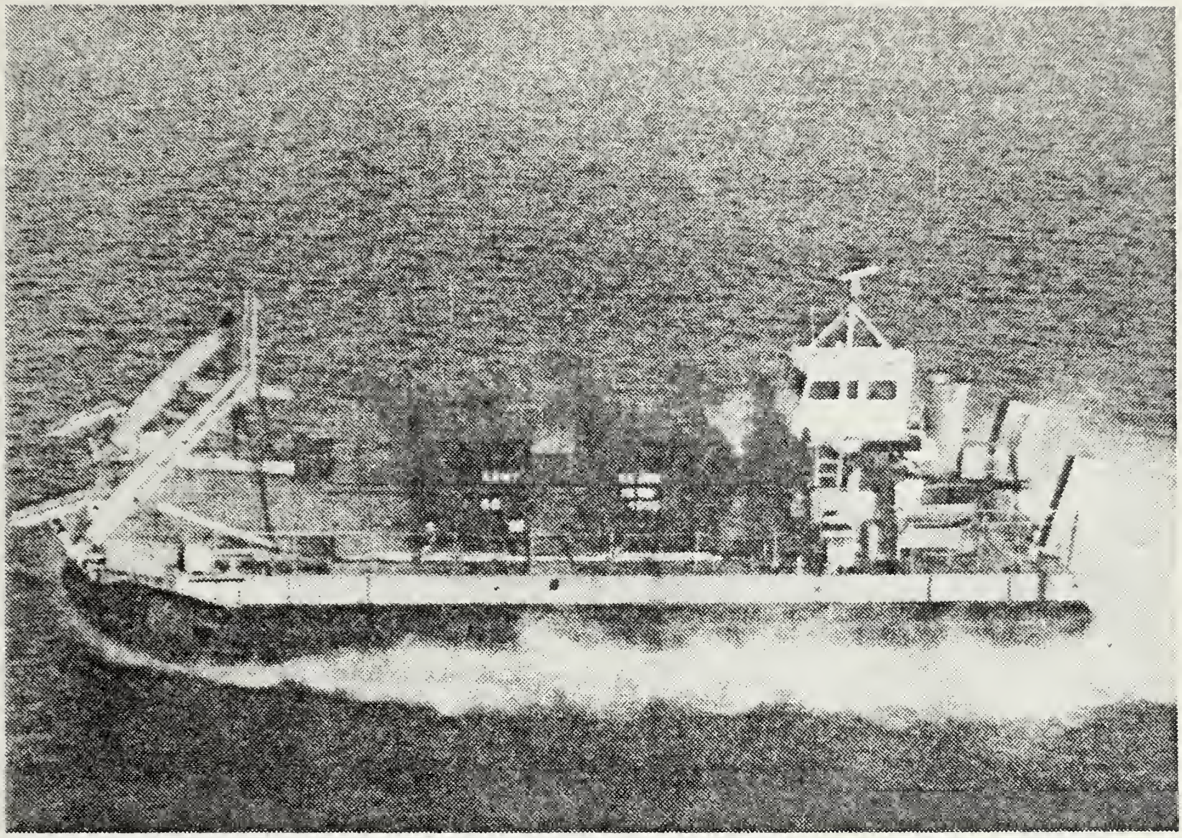


Figure 1   Bell Aerospace LACV-30 at Cruise Speed.

of such an application is the LACV-30, shown in Figure 1 operating over water at design cruise speed of 40 knots.

Air cushion vehicles were initially envisioned with high speed capability and thus the propulsion systems have evolved to meet that requirement. While it is true that the air cushion principle lends itself to high speed travel, experience has shown that typical traditional missions attempting to utilize the ACV technology involve only a small portion per operating flight hour at maximum speed. The remainder is spent at significantly lower speeds.

This aspect of actual operation sheds a different light on the ACV propulsion question. First, the air propellor, sized for a high design cruise speed, loses its appeal at

low speed, since propulsive efficiency is severely degraded. A second aspect concerns ACV maneuverability at low speeds, where aerodynamic surfaces such as rudders are ineffective. A maneuvering ACV, lacking contact with a surface, must depend on control forces which are generated at the expense of thrust power. This necessitates rotating the propellor disk or thrust generator and/or use of multiple thrustors with differential power capability. This same consideration also limits the grade climbing and descent capability of an ACV.

A third consideration focuses on the terrain-craft interaction at low speed. While at high speed an ACV largely "outruns" the spray and debris stirred up by the air cushion, at low speed it finds itself in a highly unfavorable environment. Figure 2 illustrates these conditions for an ACV operating in a beach zone. This mode of operation results in high erosion rates of the propellors and high probability of actual impact damage from foreign objects. Ancillary considerations include propellor deck space, propellor noise, and personnel safety.

At the other end of the speed spectrum are air cushion vehicle systems which can be more correctly called heavy load movers. Speeds for this type vehicle seldom exceed 10 knots. If propellors were to be used for thrust generation, they would have to be of very low disk loading and hence large diameters to exhibit acceptable propulsive efficienies. This is obviously not a practical alternative.

As a result of these system constraints, the heavy load mover ACV is often towed by tug boat over water or by caterpiller tractor over land. An alternative considered in several designs is the Surface Impulse Propulsion (SIP) concept. The SIP system involves a low pressure wheel which is mechanically driven by a propulsion motor. The concept is only practical in operations over land. Thrust performance

Figure 2   ACV Underway in a Beach Environment.

of a low pressure wheel over water is relatively poor. Figure 3 illustrates one configuration of an ACV fitted with a wheeled Surface Impulse Propulsion system.

Thus there obviously is a speed range (10-30 knots) for which there is not any one suitable propulsion concept. An alternative which may prove attractive is the marriage of the soft tire for land locomotion and the paddlewheel for water propulsion. The combination would constitute a truly hybrid all terrain propulsion system. The concept is illustrated with the aid of Figure 4 . The proposed system consists of a paddlewheel which is configured with a loosely

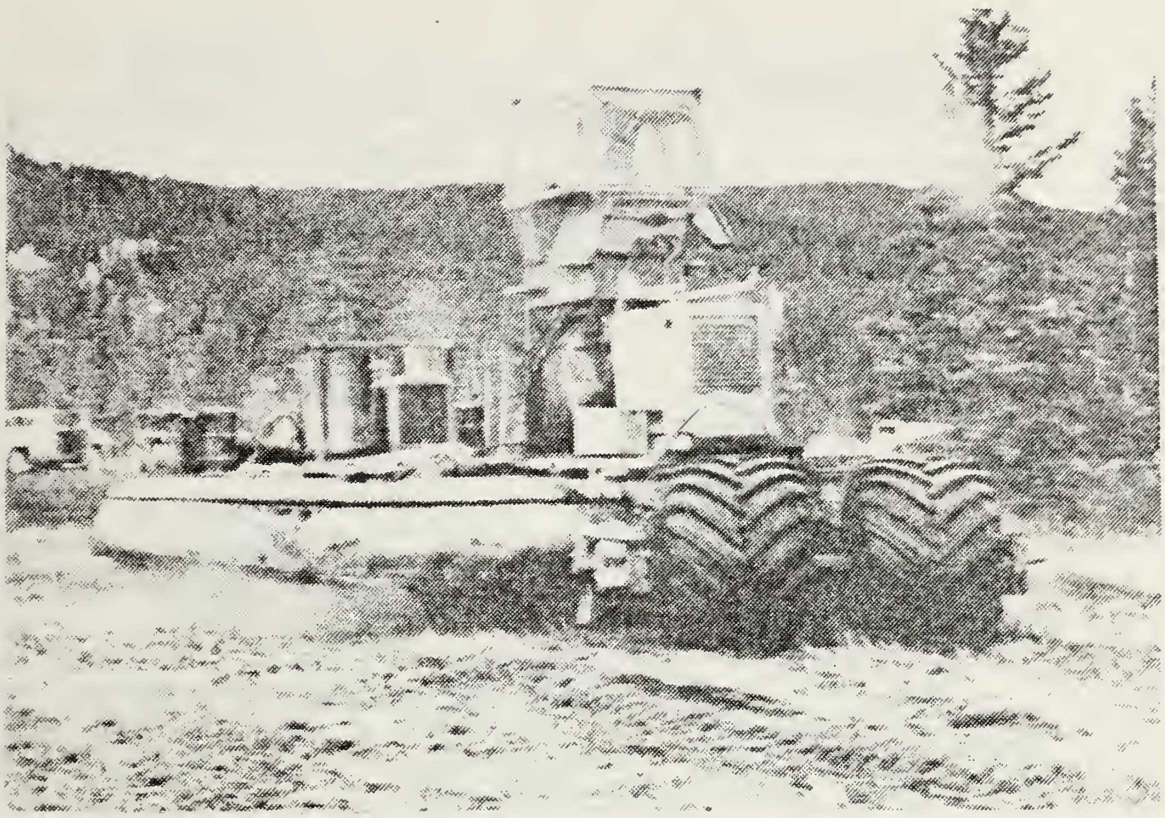
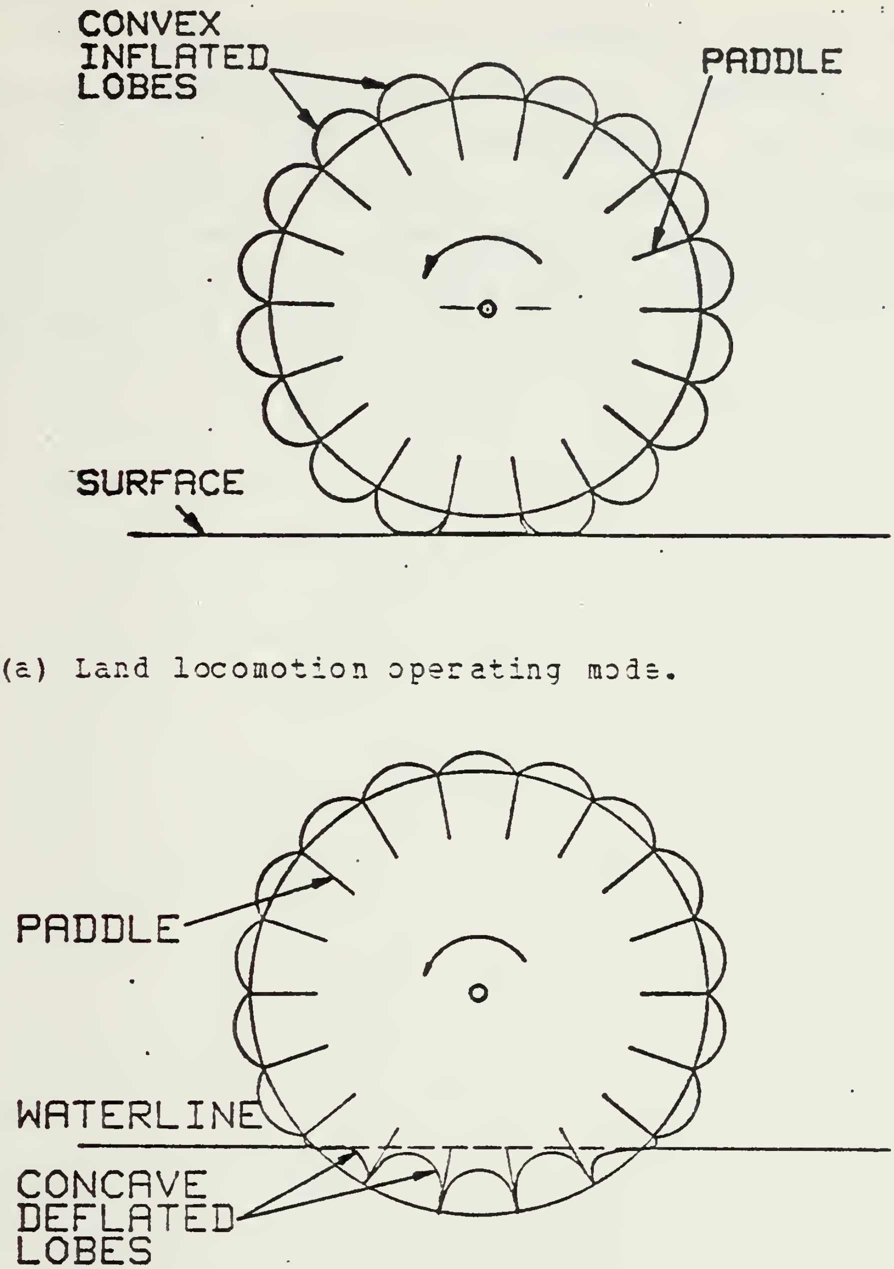


Figure 3 ACV Fitted with Wheeled SIP System.

stretched fabric material between the paddlewheel blades proper. Means are provided to selectively pressurize the interior of the wheel thus controlling the shape or deployment of the material between the paddles.

Figure 4 (a) depicts conditions for operations over land. The wheel internal pressure is increased such that the interblade fabric is put in tension and assumes a convex geometry. This effectively decouples the solid structural blades from the surface and the system behaves like a low pressure tire. In over water operation, illustrated in Figure 4 (b), the internal air pressure is decreased by the craft operator and the interblade membrane assumes concave geometry under the action of hydrodynamic forces. This



(a) Land locomotion operating mode.

(b) Marine propulsion operating mode.

Figure 4   Proposed Webbed Surface Impulse Propulsor.

allows the paddlewheel blades to engage the water and thus generate thrust.

This investigation had two goals. The first was to develop an understanding of the flow behavior and interaction with the blades of a paddlewheel type surface impulse propulsion system operating over a water surface. The second goal was to experimentally evaluate the effect of interblade webbing and wheel internal pressure on the thrust performance of a webbed SIP system.

II. BACKGROUND

A. LAND LOCOMOTION

For propulsion, vehicles designed to travel on land traditionally rely on a tractive force, or the friction between some member of the vehicle and the surface with which it is in contact. In general, land vehicles can be classified in two broad categories, on-road or off-road.

An on-road vehicle is one which is designed to follow some preconstructed or designated path. The common examples are automobiles and trains. While the particular method of generating the frictional force required and the type of path or track involved may vary widely, these vehicles have one important thing in common - the path with which the vehicle must interact will vary in its properties over only a very small range. Thus the vehicle's propulsive system is designed for operation in a relatively constant environment. If a particular natural area cannot be modified to accept the required on-road vehicle path, or if, once installed, the path becomes altered beyond design tolerances, then the on-road vehicle simply cannot operate.

The technology of on-road vehicles, while certainly not stagnant, is well understood in regard to basic concepts and is at a stage of advanced development. Research in this area centers around marginal improvement in efficiencies and more often concerns new developments in the vehicle propulsion plant than in the traction members themselves. Major improvements in the efficiencies of on-road vehicles are likely to involve engine performance, suspension, or weight reduction.

A more complex category of land vehicle, and one in which basic research is much more recent and continuing, is the off-road-vehicle, or ORV. The approach in this case is to design a vehicle which will accept interaction with the terrain as it naturally exists, rather than altering the terrain to accept a vehicle.

The primary difficulty is the lack of uniformity of terrain. Land may be made up of a very loose, grainy structure such as sand, a tightly packed solid structure such as clay, or hard, impenetrable rock. While friction between vehicle and environment is still of primary importance, this varying terrain introduces other factors which gain importance. Certain soils may stick to the vehicle, bogging it down and clogging the operating mechanisms. Some soils pack under pressure, while others give way, allowing the vehicle to sink in. Certain soil types have a rough characteristic very supportive of friction, while others may have a very low frictional coefficient, allowing easy sliding of vehicle propulsive members. In addition, moisture content can change the characteristics of a soil type quite drastically over relatively short time.

Bekker [Ref. 1] has classified various soil and terrain types and conditions with respect to two primary properties, cohesiveness (or plasticity) and friction (or graininess). This classification allows the varying terrain to be categorized as to its interaction with the tractive member of an ORV.

An understanding of the reaction forces exhibited by various terrain types allows the choice of the type of traction member most suited to required terrain travel. Two common means of propulsion of ORVs are wheels with tires and rolling tracks. Wheeled vehicles may be agriculture related tractors and trucks, recreational dune buggies, or the Lunar Rover used to transit the moon's surface. Tracked vehicles

include large construction bulldozers and cranes as well as military tanks.

Other factors important in the performance of ORVs, both tracked and wheeled, are the resistance to motion imposed by the terrain due, for instance, to its cohesive nature, and the flotation, or lack of sinkage afforded by the terrain, allowing the vehicle to interact only with a shallow surface layer of soil and not to sink. The latter would require physically moving the soil mass in order to proceed. Further work by Bekker and by Wong [Ref. 2] with respect to resistance to motion and to flotation have led to some empirical relationships for predicting the performance of both wheeled and tracked vehicles over widely varying terrain. Figure 5 shows a summary of some vehicle types which Bekker predicts will have the best mode of locomotion for different soil types [Ref. 3].

Advances in technology of materials have aided in the design of wheeled ORVs. Tire technology advances have made possible very large tires which have a large contact area and very low internal pressure. This combination reduces sinkage. Extremely large, low pressure tires are now available. A 20-foot by 6-foot tire with internal pressure of 20 psia and 500,000 pound capacity has been fabricated using a curing process [Ref. 4]. Tires up to 40-foot diameter with internal pressure less than 5 psi are technically possible.

The use of articulated or flexibly sectioned vehicles has greatly enhanced ORV capability to climb steep grades and to overcome obstacles. Bekker and others have built and tested prototype vehicles to study this aspect of performance. Much of this research was done in conjunction with development of the Surveyor Lunar Roving Vehicle (SLRV) [Ref. 5] and other similiar vehicles intended for use as a part of space exploration programs.

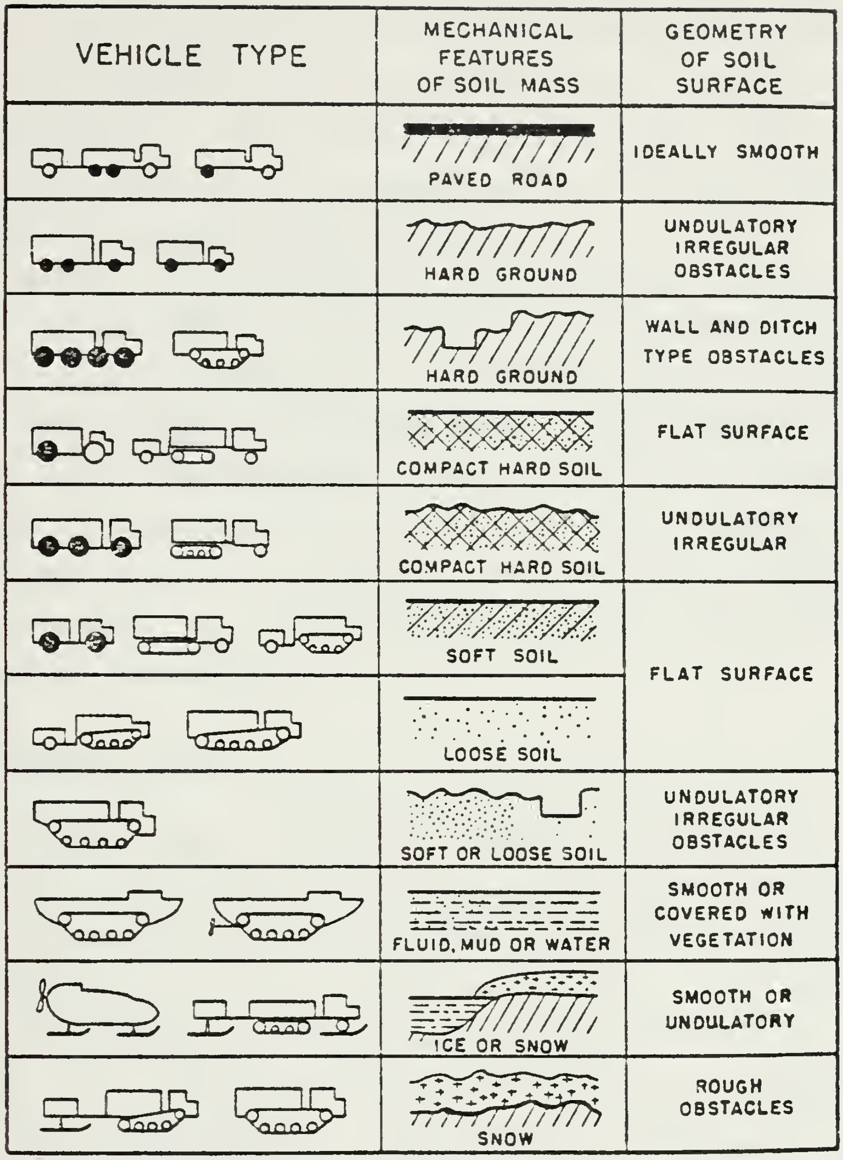


Figure 5 Vehicle Suitability to Terrain.

B. MARINE CRAFT

Marine propulsion relies in most cases not on friction (more appropriately labelled drag in a fluid environment) but rather on change in momentum of the water in contact with the vehicle's propulsive member. This momentum change can be applied at the free surface or submerged.

The earliest marine propulsor was undoubtedly the oar, powered by human energy. As vehicle size and weight increased, the need for more thrust increased. The eventual development of paddlewheel propulsion was actually a conceptual extension of the multiple oar idea. The paddles, however, were arranged in a geometry more convenient for the application of a mechanical driver.

Development of subsurface propulsors, first rotating screws and then bladed propellors with increased efficiency, eclipsed paddle propulsion. Propellors are also, in general, more material conservative. The propellor is thus in general much smaller and contains much less material than a paddlewheel producing the same thrust. These advantages of propellors led to a virtual abandonment of paddlewheel propulsion except in a few special cases. One exception is shallow water operation.

C. AMPHIBIOUS CRAFT

Amphibious craft, vehicles that are required to operate equally over land and in water, present additional difficulties. In this case, the propulsion system must operate satisfactorily not only on land and water, but must also be capable of transiting the marine-land interface.

Design of amphibious vehicles can be classified as ground-up or conversion. In theory, ground-up design is more attractive since it allows the designer total freedom in selecting subsystems and should result in a completely new and fully optimized vehicle. Conversion design begins with an already proven vehicle from one medium, usually land, which is adapted to operate in the second medium.

The earliest attempts at amphibious vehicle design were considered ground-up. In reality, however, these craft involved automotive technology augmented and altered as

necessary to accomplish flotation and some degree of marine propulsion. Typical characteristics of some of the early ground-up designs are summarized in Table I [Ref. 6].

TABLE I

Ground-up Designed Amphibians

NAME	TIMEFRAME	DESIGN/OPERATING CHARACTERISTICS
Jagger	1926	Used Ford Model-T components Chain Drive to rear wheels Removable paddlewheels Max. water speed 4 mph
Jagger-Honukai	1928	Used Ford Model A components Twin propellors above rear axle Max water speed 5 mph
German Amphib. Scout	1944	Wheel drive on land Single screw propellor Retractable outboard drive Max water speed 5 mph
Roebling Alligator	1943-1948	Track propelled land and water Max water speed 3 mph
Landing Vehicle Tracked	1945-1955	Track propelled land and water Shrouded track Good water performance

During WW II, conversion became the dominant, although not exclusive, method of design. The missions for these vehicles included the movement of men and machinery ashore from ships during amphibious assault and movement inland

over sand, rock, mud, and snow once ashore. Several wheeled versions, primarily converted jeeps and trucks, met with relative success for beach assault, and a class of tracked amphibians, designated "Weasels", was developed for snow and muddy terrain transit. Table II is a summary of some successful conversion designs [Ref. 7].

TABLE II

Conversion Designed Amphibians

NAME	TIMEFRAME	DESIGN/OPERATING CHARACTERISTICS
Temporary Conversion 1/4 ton	1941	Converted 4X4 1/4 ton truck Removable floats for buoyancy Shrouded tires for thrust Unimpeded shore operation Max water speed 3 mph
M-29C Weasel Amphibious Cargo Carrier	1941	Converted M-29 lt. cargo carrier Permanent watertight hull Track propulsion Extensive track shrouding Rudder steering
Ritchie T-6	1942	Converted M-4 medium tank Large, removable shrouds/pontoons Good water performance
DUKW	1941-1948	Converted 6X6 2-1/2 ton truck Wheels,land appendages in "wells" Screw propellor driven Max water speed 6 mph Most widely used amphib. in WWII

Review of Tables I and II indicates another method of classification of amphibious vehicles, single or multiple mode of propulsion. It is observed that the multiple mode

is the more predominant method of propulsion. Typically these craft have some sort of wheeled system as the tractive device on land and a propellor or waterjet for marine propulsion. This type of craft is generally easier to design since the propulsive means on land and in water are quite different and somewhat independent and each can be tailored to its own mission. There are, however, some distinct disadvantages. The wheels required for land operation not only serve little purpose in the marine environment, but actually increase vehicle drag as bulky appendages, inhibiting the marine performance. The propellor, on the other hand, must generally be placed very close to the vehicle hull and in some protected "well" to avoid damage during landing and land operations. Alternatively, it must be made retractable, complicating the mechanical structure and increasing cost, maintenance, and chance of mechanical damage or breakdown. The changeover point from marine to land propulsion also poses operational problems. Landfall can become an ill-defined and hazardous maneuver. Additionally, inclusion of two complete propulsive systems, only one of which is in use at a time, is certainly costly, weight and volume critical, and very inefficient.

The only vehicles to utilize a single mode of propulsion during this period were tracked amphibians. It was noticed on early tracked vehicles that the track was capable of "pushing" some water thus providing some thrust, so that once flotation of the vehicle was achieved, all that was left was to improve the paddling efficiency of the tracks. This was accomplished through attachment of small paddles, or "grousers". In order to avoid damage during land operation, these grousers were manufactured of flexible material, designed to be retractable, or attached to protrude inward rather than outward from the track.

This type of design has worked well as a land vehicle but only marginally in the marine environment. The major losses associated with this type of paddle motion are (1) turbulence and backflow around the paddles and (2) components of momentum change in directions other than that required for forward thrust. The return or forward moving portion of the track produces negative thrust or drag if it is submerged or water "carryover" if above the free surface. Vertical thrust, negative and positive, is applied at water entry and exit positions respectively. The spray or roostertail exhibited by many tracked amphibians is evidence of the vertical components of momentum transfer with this design. A typical track design is illustrated in Figure 6 [Ref. 8].

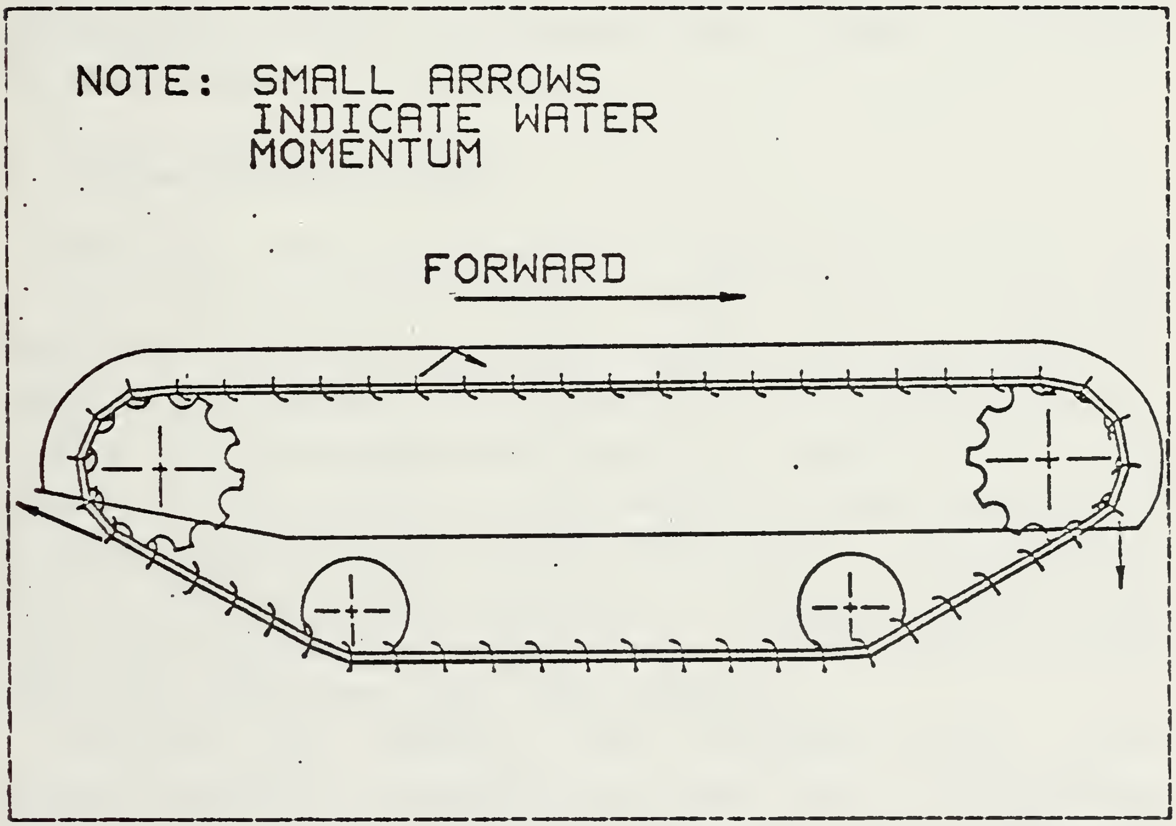


Figure 6 Typical Tank Track Design.

Numerous accessories have been introduced to reduce these losses. Most appear at least partially successful but generally cause further design or operational complications and become themselves susceptible to damage. Optimal hydrodynamic grouser design must be compromised with the requirement for resistance to damage. Side tracks around the track drive wheels are used to reduce hydrodynamic turbulence, but easily clog with mud and weeds. Stripping fenders to remove entrained water from the forward track, deflectors to reverse this forward flow at the front of the track, and small design clearance between the return portion of the track and the hull of the vehicle have all been used with some success to improve efficiency, but all increase the risk of damage, fouling, or clogging during operation in other than clean water. Kilgore [Ref. 9] provides hydrodynamic analysis of several track designs and add-ons for improvement of efficiency.

D. SURFACE EFFECT VESSELS

The most recent development in amphibious craft has been in the area of surface effect vessels (SEVs). While the amphibious mission has been defined as with previous vessels, the approach to the problem is radically different. An SEV, which generates and floats on a cushion of air, can not, in a strict sense, be considered to operate in water or on land. Nevertheless, the SEV functions as a viable alternative to a traditional amphibian. Several of the vehicles have been successfully operated over a wide variety of land and water conditions, with much success.

The SEV has, however, some drawbacks. While it has proven remarkably successful over open water in high-speed operations, the vehicle has experienced serious maneuverability and braking problems as well as grade climbing

limitations during low-speed land operations. Another drawback has been the persistent spray of water and debris around the craft due to perimeter cushion air discharge.

Auxiliary retractable wheel systems have been designed and analyzed for use as a tractive device during low speed, high grade angle operations. Alternate configurations for traction wheel propulsion have been proposed. [Ref. 10]

E. COASTAL AND RIVERINE CRAFT

During military operations in Southeast Asia in the 1960's, small river operation proved extremely difficult for propeller driven craft and research was undertaken on a paddlewheel propulsion system for small, shallow draft vessels [Ref. 11]. The research was somewhat empirical in nature, utilizing a number of radially bladed paddlewheels of from twenty to thirty inch diameter with up to twelve paddles. The wheels were mounted in a manner to have a manually adjustable immersion level and to be manually steerable. They were tested as the propulsor on sixteen to twenty-one foot aluminum utility boats.

While propulsive efficiency was not considered in detail, the overall results were very promising due to the ease of operation, good maneuverability, and environmental versatility of the test craft. Specifically, the paddlewheel propulsion system provided the following results: good maneuverability by turning the entire wheel assembly, excellent control of the amount of thrust produced by varying the immersion depth of the paddles, an ability to cross mud and sand bars by the "digging in" of the paddles to act like a track and push the vehicle through the mud, and lack of fouling of the wheel even when operated in thick weeds and brush. The primary problems associated with this experimental propulsion system are the classic ones related to

paddlewheel propulsion and common to tracked amphibian systems, vertical components of momentum change and entrainment of water in the forward direction. This results in spray and a decrease in potential efficiency. A partial solution in this case was once again a deflector or "spray shield" installed across the upper portion of the wheel.

Research to establish optimum design parameters was conducted on a semi-submerged paddle track (SSPT) propulsor. Tow tank thrust measurements were made on a series of tandem rectangular plate propulsors, varying plate aspect ratio, distance between plates, and speed of the track through the water. [Ref. 12]

In some designs, the blade entry and exit problem has been addressed by "articulating" the blade. This mechanical "feathering" of the blade allows "clean" entry and exit and minimizes spray generation. The system, however, increases in mechanical complexity and decreases in reliability.

III. TEST PROGRAM

In the formulation of the test program it was realized that there would be uncontrollable variables and synergistic interaction between the various parameters. To at least partially circumvent this difficulty, it was decided to develop a data base and a set of fluid behavior observations for a conventional unwebbed paddlewheel model. Thus the experiment was designed for rapid fitting out of webbing and minimum geometry changes between webbed and unwebbed configurations.

A. OVERALL SYSTEM

The overall test system consisted of an existing test tank at the Naval Postgraduate School, the carriage or traversing system, the paddlewheel support structure, the paddlewheel or surface impulse propulsor, and the instrumentation and data acquisition system. An overall perspective is illustrated in Figure 7 .

B. SURFACE IMPULSE PROPULSOR

The paddlewheel propulsor consisted of 21-inch diameter sidewalls of 1/2-inch plexiglass, tapered along the outer edge. The system was fitted with 18 equally spaced, radially oriented blades 12 inches wide with a 3 inch chord, open along both the inner and outer edges. The paddles were fabricated from plexiglass 1/8 inch thick and were recessed 2 inches from the sidewall outer edge to two dimensionalize the flow in the vicinity of the blades. Over the outer edge of each blade was attached a 1/8-inch brass channel to increase longitudinal stiffness of the blade and to provide a means of attachment for the webbing material.

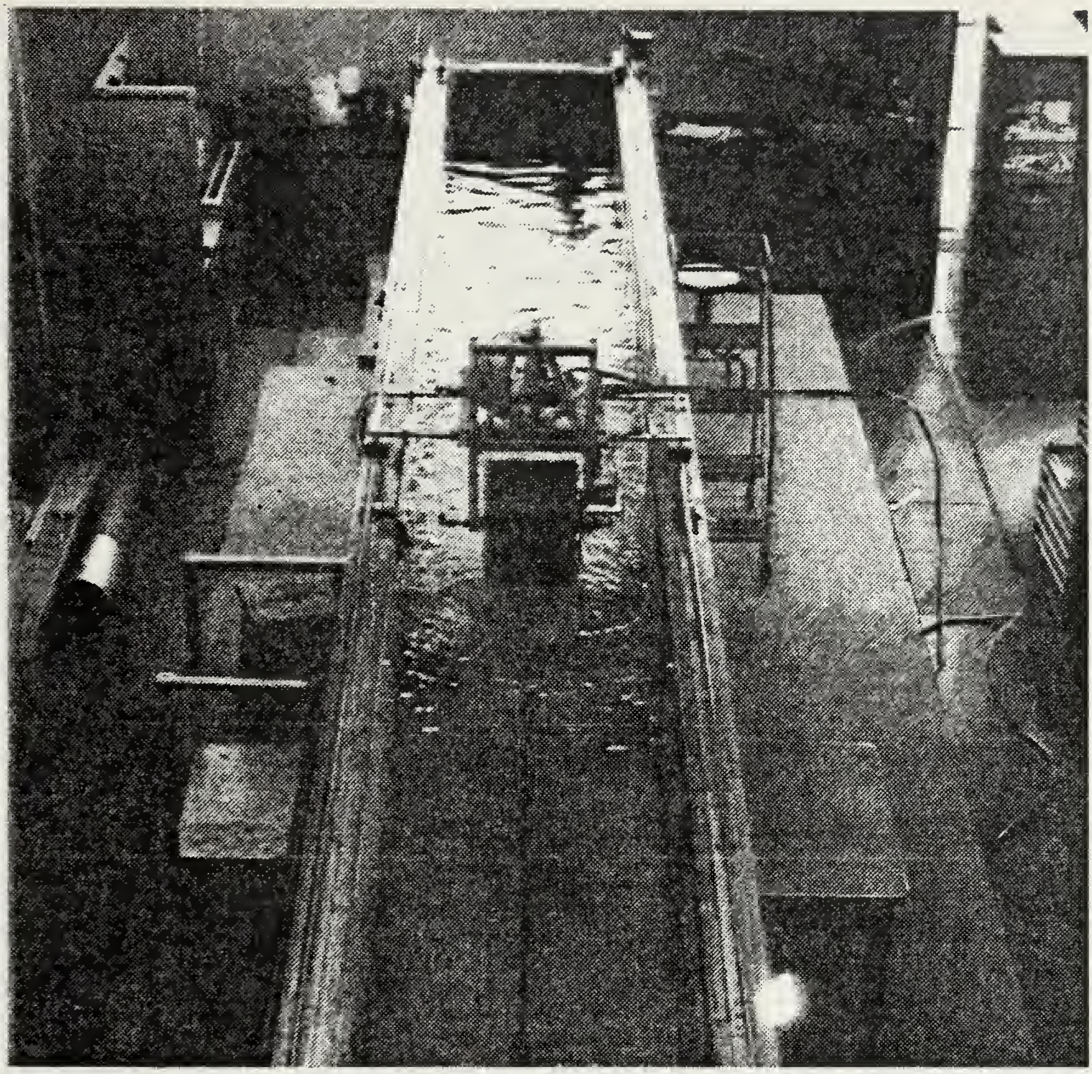


Figure 7 Paddlewheel Propulsor System.

The webbing was a lightweight, airtight, flexible nylon fabric commonly used in the manufacture of spinnaker sails. It was cut to a width of slightly greater than the 12-inch paddle width in order to minimize gaps between the material and the paddlewheel sidewall. The material was cut as a continuous lengthwise piece and attached across the edge of each paddle allowing a uniform amount of slack material in each blade cavity. Web material was cut to provide for two ranges of web length.

The wheel rotated on a hollow, stationary shaft through which the wheel air supply was introduced. The shaft also provided a sensing port for measuring the internal air pressure. A fine mesh wire screen was fitted over the shaft along the supply end in order to more evenly diffuse the air into the wheel interior. The entire wheel was held rigidly together by four equally spaced rods bolted through the sidewalls.

The propulsor was gear driven through a double reduction of about 80:1 by a small (approximately 0.1 hp) DC motor. Paddle immersion depth was varied by varying the tank water level. Changes in bottom reaction as tank level was varied were considered negligible due to the small fraction of total tank depth to which the paddles were immersed and the relatively shallow nature of the interactions observed.

C. CARRIAGE ASSEMBLY AND FRAME

A frame was constructed to interface between an existing tank carriage and the propulsor. The frame and carriage carried the appropriate wheel drive mechanism, transducers, and power interface.

The basic frame was constructed of 1 1/4-inch aluminum channel rigidly mounted to an existing tank platform and to the paddlewheel shaft. The tank platform was configured to ride on four roller bearings on tracks along the top of the tank and was powered by continuous loop cables attached to each side of the track and pulley driven by a controllable speed AC motor. A series of floating pivots was configured to allow the attachment of a force sensor in the horizontal direction. A plexiglass wiring board was attached for mounting and connection of all sensors.

D. DATA ACQUISITION

The experiment was designed for automated data acquisition to increase the speed and accuracy of measurement of required data during the short duration of each test run. Acquired data included horizontal thrust, internal air pressure when operated with the webbing material in place, forward speed of the carriage, wheel rpm, and voltage and current of the wheel drive motor.

Thrust was measured by a force gage block attached to a floating beam. To this same pivot arm were rigidly attached the wheel drive motor and the wheel shaft. Rotating on the shaft were the propulsor and its drive gear. Figure 8 (a) illustrates the arrangement. The forces external to the pivot arm/propulsor system were reactions at the pivot, gravity, reaction of the force block, and components of reaction due to water contact with the immersed blades. The summation of horizontal components of the water reaction or thrust forces on the immersed blades has been replaced in Figure 8 (b) with an equivalent thrust force located at the center of the immersed portion of a vertically oriented blade. Summing moments about point O, the pivot, to insure equilibrium of the pivot arm with regard to rotation about O, the measured force of the force block was used to calculate the instantaneous thrust generated by the propulsor.

Internal pressure was monitored through a pressure transducer mounted on the sensor board and attached by plastic tubing to one end of the hollow wheel shaft. Platform forward speed and position were measured by a velocity and position transducer mounted on the tank endwall and attached to the carriage by a stainless steel cable. Wheel rpm was measured as a function of the DC voltage generated by a small DC generator geared to the paddlewheel. Drive motor voltage and current were measured directly.

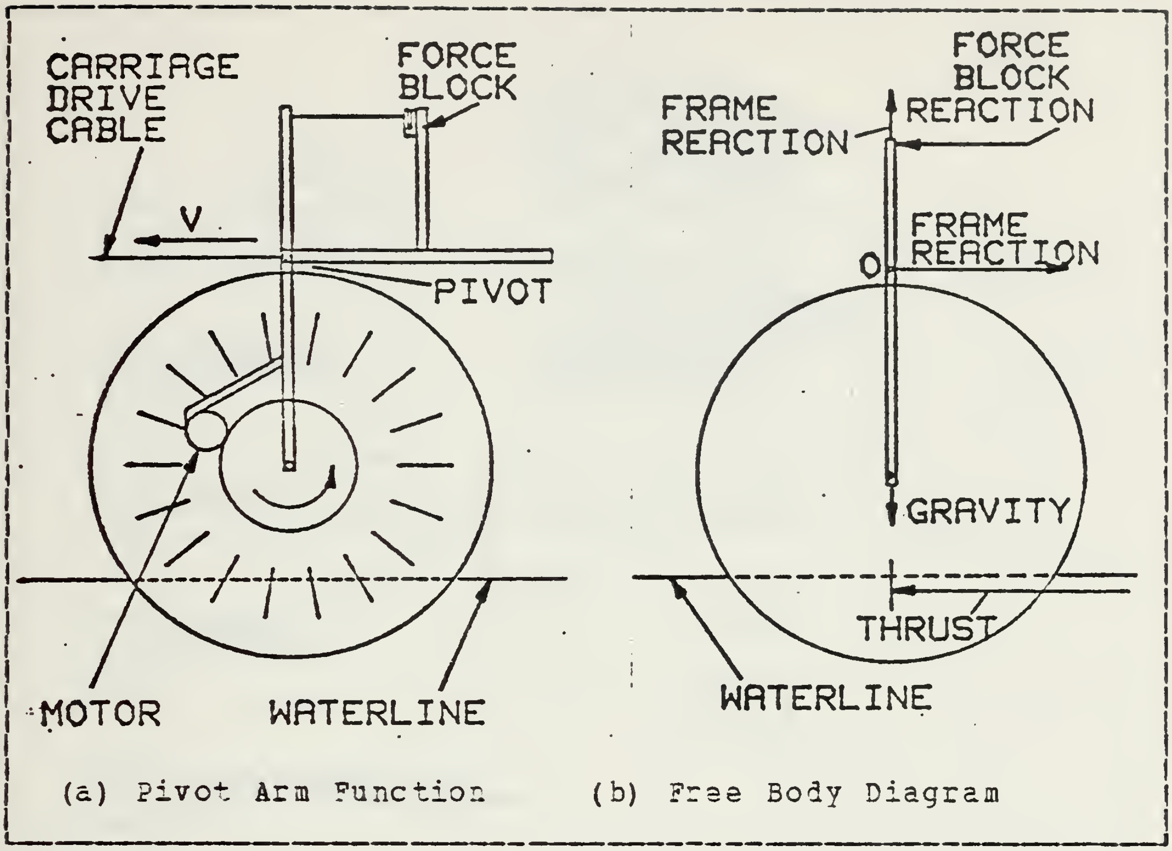


Figure 8 Measurement of Propulsor Thrust.

All analog signals were then processed through an analog-digital convertor to a microcomputer for storage and processing. Figure 9 is a schematic of the data acquisition system. Details and associated accuracies of the sensors and equipment used are presented in Appendix A.

The actual data for each run was acquired at identical positions in the tank. This was achieved by triggering the data acquisition sequence from a preselected value of carriage position as sensed by the position transducer. During each test run, the transducers were surveyed a number of times (approximately 40 passes per second), an average computed, and the data point displayed at the printer.

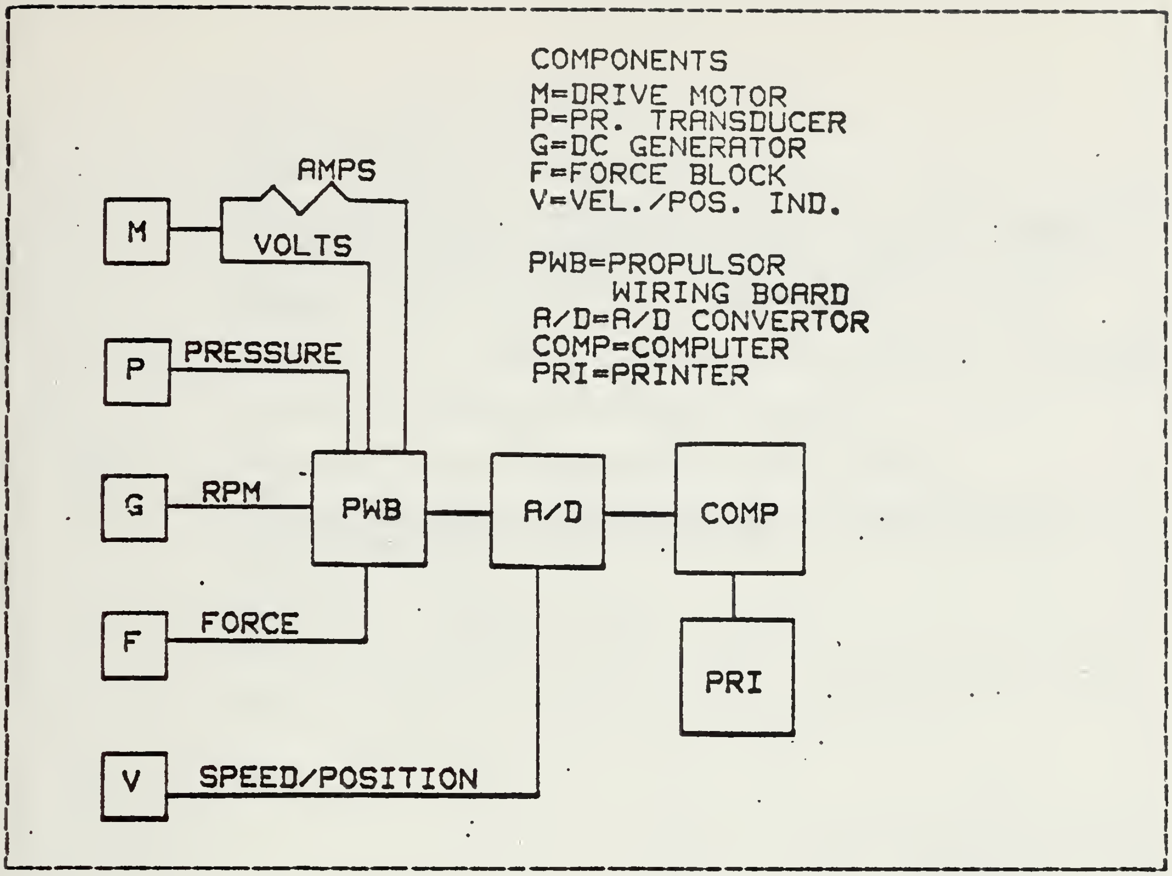


Figure 9 Data Acquisition System Schematic.

E. TEST SEQUENCE

The paddlewheel propulsor nomenclature is defined as illustrated in Figure 10 . Complete system nomenclature and constants are presented in Appendix B. These variables have been grouped into several convenient parameters. B/H, D/H, and R/H define the geometry of this particular system. Percent immersion, defined as D/H X 100%, represents that portion of available blade height (and hence that portion of available blade area since B is held constant) that is statically immersed. While meaningful for this particular geometry only and not necessarily having the same effect for different values of B/H or R/H, it serves as a means of

B	Paddle beam (12 inches)
H	Paddle height (3 inches)
R	Effective wheel radius, measured to the midpoint of the immersed portion of the paddle, inches
D	Maximum static draft of paddle when at rest, inches
L	Blade tip to blade tip chord distance (3 inches)
W	Blade to blade web length, inches
RPM	Measured wheel revolutions per minute
U	Average paddle forward velocity calculated at the midpoint of the immersed portion of the paddle, ft/sec
V	Carriage forward speed, ft/sec
P	Internal wheel pressure with web applied, psig
T	Model generated horizontal thrust, lb

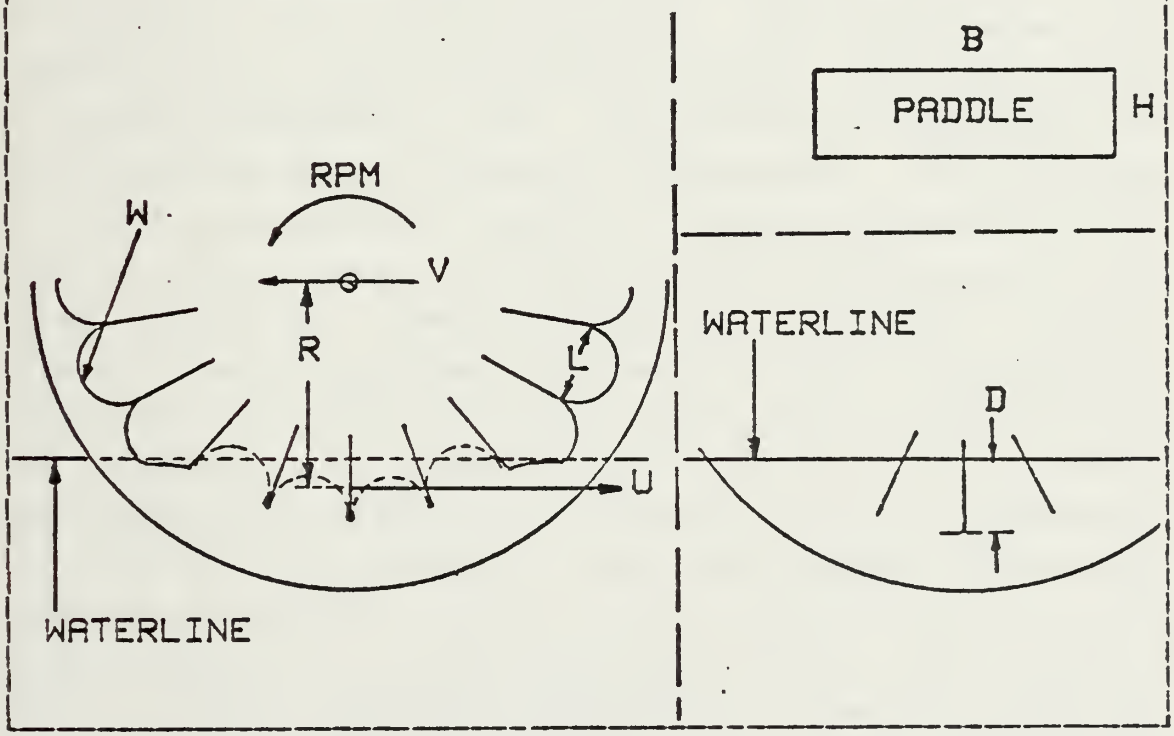


Figure 10 Paddlewheel Propulsor Nomenclature.

comparison of performance with variations in immersed area. Due to the surface nature of the propulsor/water interaction and the dominance of immersion depth D over other geometric dimensions on this interaction, Froude number based on D was examined as a parameter for comparison of thrust performance. The Froude number range examined, 0.35 to 2.44, is typical of that encountered in some common full scale paddlewheel applications for large, shallow-draft vessels [Ref. 13]. A summary of key parameters is presented in Table III .

The data was obtained in a systematic manner. A typical sequence is as follows. A particular wheel geometry, i.e. unwebbed or webbed, was installed and checked for satisfactory operation. A percent immersion was selected, internal wheel pressure was set, and carriage speed was chosen. Thrust was then measured at this carriage speed for a series of different wheel rotation speeds. The sequence was then repeated over a range of carriage speeds, then over a range of internal pressures, etc. The choice of web length, W, was controlled by two opposing requirements. The first was to provide sufficient length to allow deflection of the webbing concave inward and normal blade interaction with the water during the immersed phase of operation. Second, however, was a requirement imposed by this two dimensional model that the convex inflated lobes remain within the wall rim diameter to provide a seal with the wall and allow enclosure of the internal air without further attachment of the web to the sidewall. The two lengths chosen were selected to provide insight into the degree of balance between these two conflicting requirements. The range of wheel internal pressures examined was chosen to allow the hydrostatic/hydrodynamic pressure to interact favorably in determining the shape assumed by the webbing lobes at different speeds and immersions. For the immersion range

TABLE III

Important System Parameters

B/H	Ratio of paddle beam to height (4 for model)
R/H	Ratio of effective radius to paddle height
D/H	Ratio of immersed depth to paddle height
% slip	Percent difference in paddle speed and carriage speed $\% \text{ slip} = (U-V)/V \times 100\%$
% imm.	Percent of available single paddle depth that is statically immersed $\% \text{ immersion} = D/H \times 100\%$
CT	Model thrust coefficient based on static frontally projected wetted area of a single paddle $CT = \dfrac{2T}{\rho (V)^2 (B \times D/144)}$
FR	Froude number based on paddle immersion (D) $FR = \dfrac{V}{\sqrt{g\ (D/12)}}$

studied, hydrostatic pressure varied from 0 at the surface to 0.108 psig at the deepest immersion. A range of 0 to 0.10 psig was therefore chosen in an attempt to quantify optimum operating pressure as a function of immersion and

speed. A list of the variables examined and the ranges over which they were studied is presented in Table IV.

TABLE IV
Range of Variables Examined

Parameter	Range of Values
V, ft/sec	1, 2, 3, 4
P, psig	0, 0.05, 0.10
W/L	unwebbed, 1.33, 2.00
% Immersion	33, 67, 100
% Slip	0-100%

A total of 39 different configurations of webbing, pressure, immersion, and speed were studied, with between 4 and 15 data points recorded for each configuration at various values of percent slip. A total of 243 data points were recorded.

IV. DISCUSSION

The original data points are presented in tabular form in Appendix C. A second order polynomial was applied to the data. These curves, with the original data points superimposed, are presented in Appendix D.

A. UNWEBBED PROPULSOR

The basic, unwebbed paddlewheel propulsor was well characterized by the initial series of data runs. It was observed and confirmed by the curves of Appendix D that generated thrust increased with increasing percent slip for all test configurations. In general, this increase was approximately to second order.

In the absence of other effects, thrust would be expected to increase with increasing rotor speed, since water is processed at a faster rate. This increases the "mass flow rate through the system" and increases the total momentum change. This was plainly observed at 33% immersion. Figure 11 illustrates, however, that thrust did not increase uniformly with speed and that the rate of increase with speed was different for different blade immersions. At 100% immersion, thrust was actually seen to peak then decrease with increasing forward speed.

The classic problem of paddlewheel propulsion, the entrainment of water as the blades exit the surface, was vividly observed in Figure 12 . This highly dissipative condition was aggravated at increased rotor speeds and at higher blade immersions, and certainly detracted from the potential thrust generation.

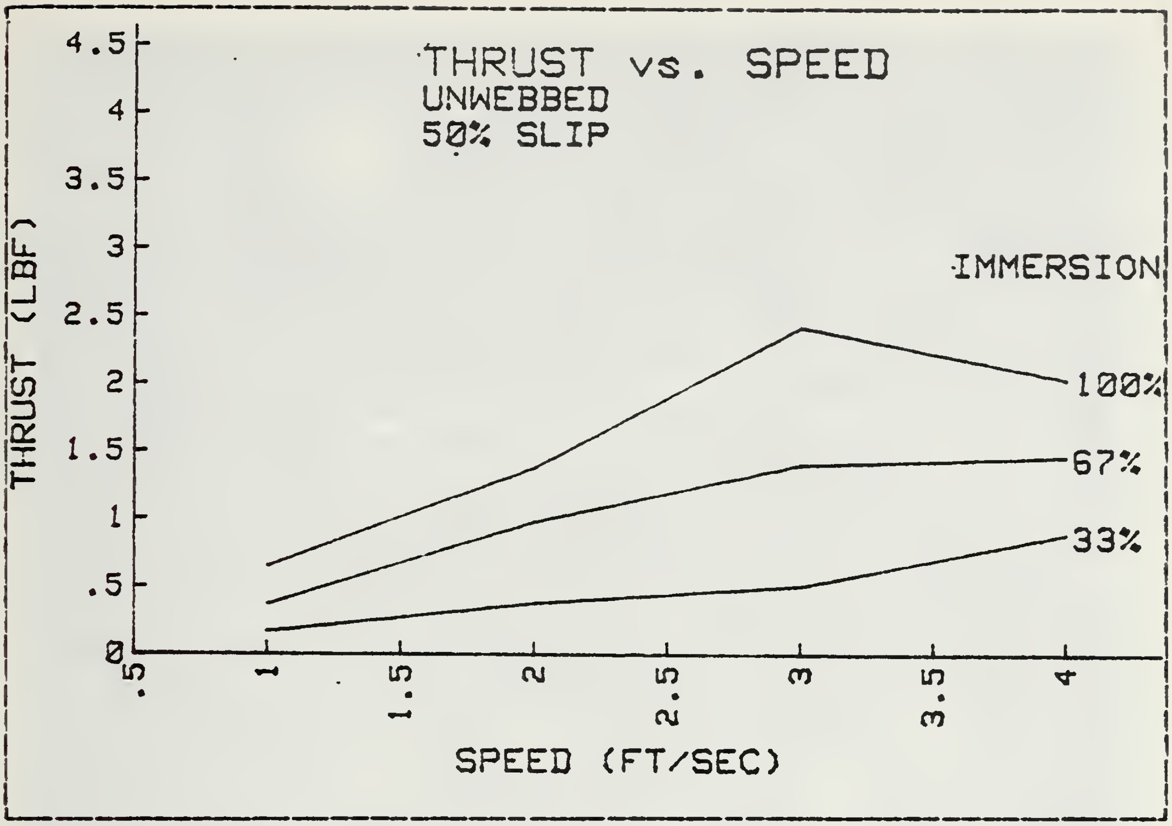


Figure 11 Thrust vs. Speed for Various Immersions.

Several different effects are thought to be responsible for this behavior. These can be related to a change in the effective blade-water contact area under "dynamic" conditions. Fluid-blade interaction is considerably more complex and cannot be adequately described by considering only static projected area of a particular blade.

First, movement of the paddle through the water caused a buildup or "wave" of water ahead of the blade on its positive pressure side. This phenomenon increased the effective area of contact and conceptually increased the generated thrust. The effect could be expected to be more pronounced at higher speeds and higher percent slip. The phenomenon was visually observed and is shown in Figure 13 .

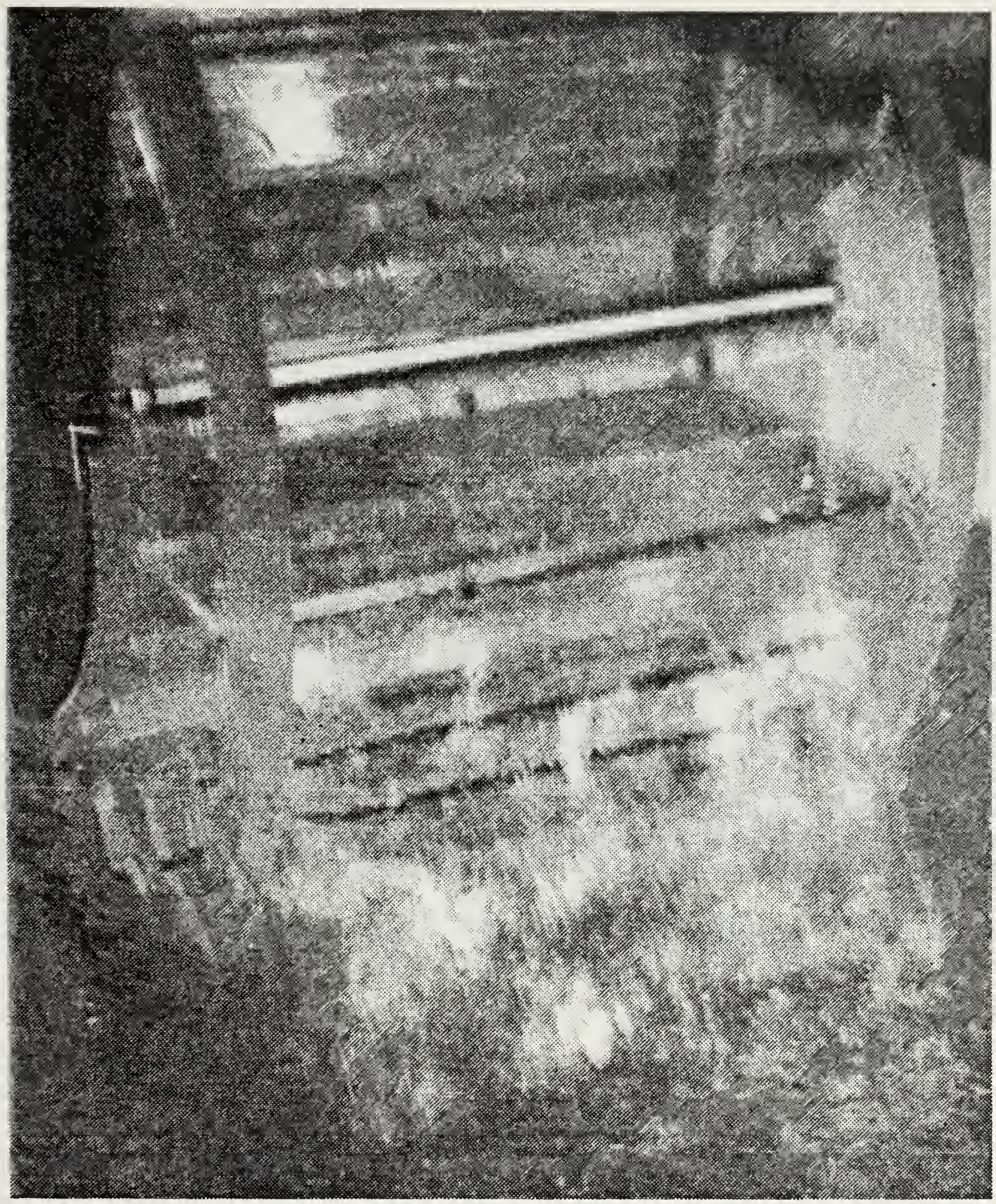


Figure 12 Entrainment of Water by Paddlewheel Blades.

The positive significance of the wave effect was only valid until the wave height reached the top of the paddle, at which point excess buildup simply spilled over the blade

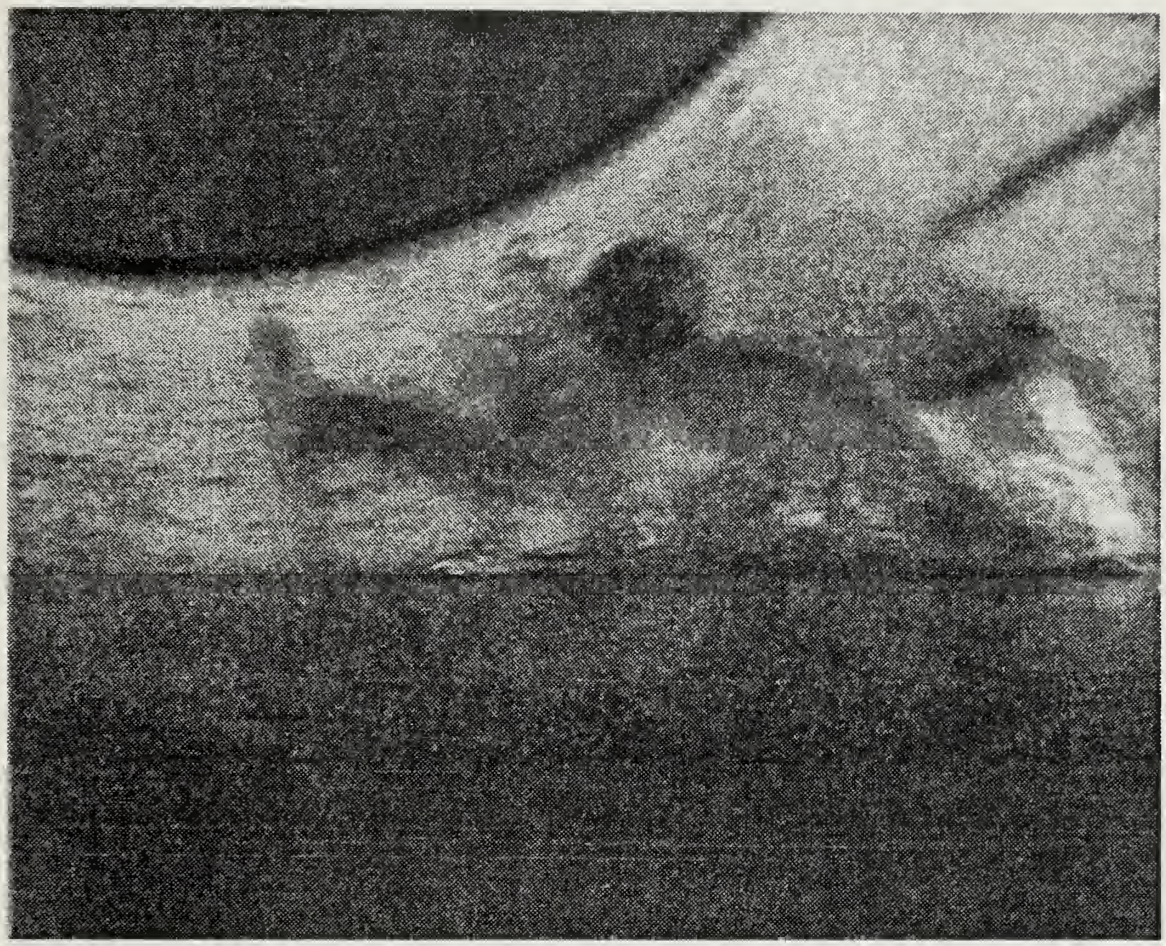


Figure 13   Wave Effect Generated by the Paddle Action.

top. It was this consideration that, in all probability, was responsible for the fall-off in thrust indicated in Figure 11 .

Another observed effect which could be expected to alter the effective blade area was the entrainment of ambient air on the blade suction side during water entry. This problem was minimal at 33% blade immersion, but was notably observed at 67% immersion and increased dramatically at full blade immersion. As expected, the entrainment was much more severe at higher rotational speed and hence higher slip percent. It was also aggravated at higher forward speeds.

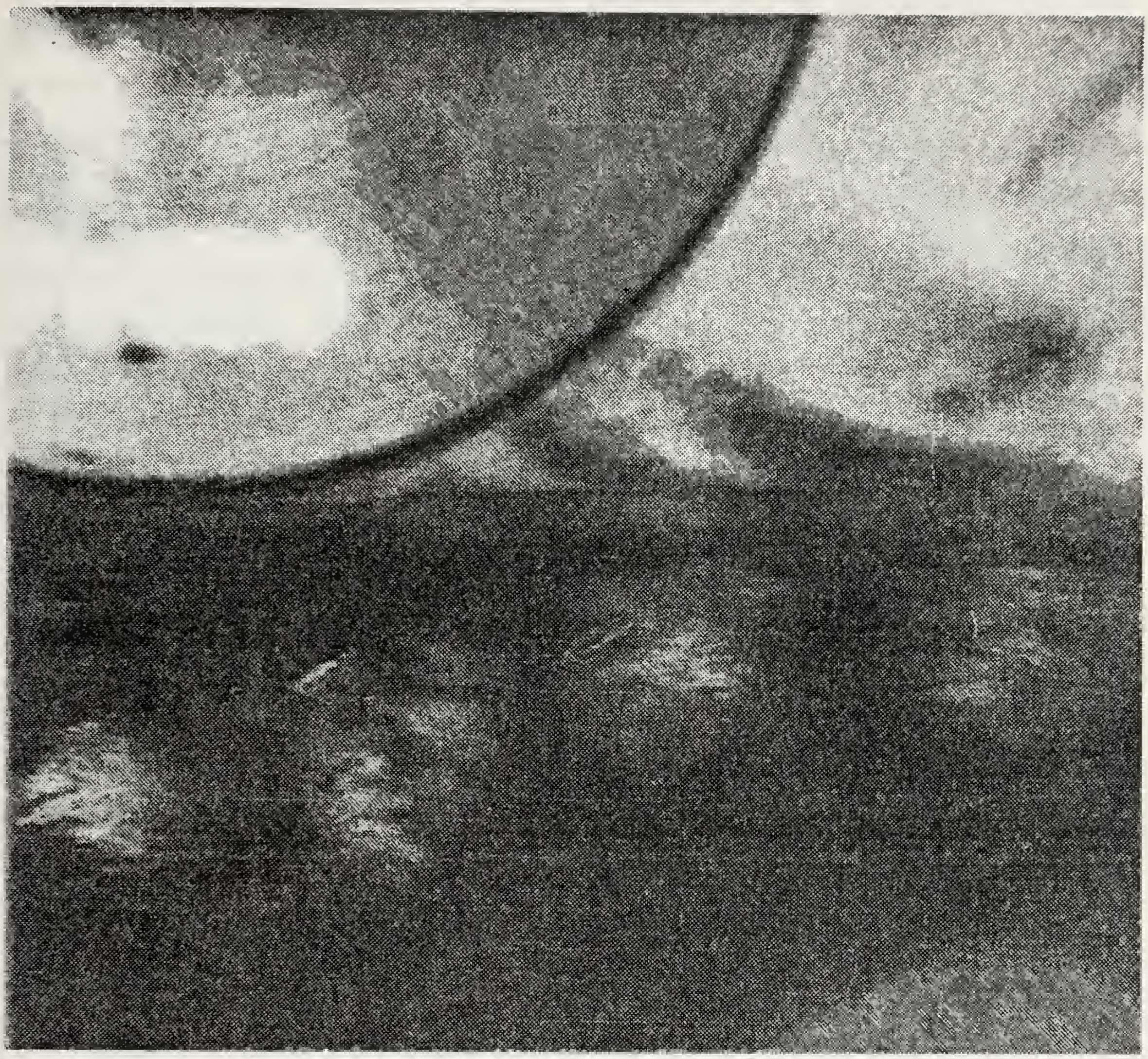


Figure 14 Air Entrained in Blade Cavities.

Figure 14 shows the swirling vortex action. It was observed that the trapped air remained as a distinct core in the interblade zone and that this core carried over into the blade exit area where it "exploded", generating turbulence.

It can be conjectured that the combination of these two effects altered the effective interaction area and thus altered the thrust generated. The vortex action appeared to be responsible for an effective area decrease and the

accompanying loss of thrust as speed was increased. This was valid for all blade immersions. An offsetting effect, however, was the increase in effective area due to the wave buildup on the pressure face. This trend also increased with speed but became less significant at higher blade immersion. At 100% immersion this favorable effect disappeared altogether. Under these conditions, the interblade flow phenomenon was dominated by losses due to the vortex core and the thrust was seen to decrease.

Curves relating thrust coefficient to Froude number further illustrate these trends. It is seen in Figure 15 that while thrust coefficient dropped off with increasing speed at all levels of immersion, it did so more rapidly at higher immersions, where the beneficial effect of the wave

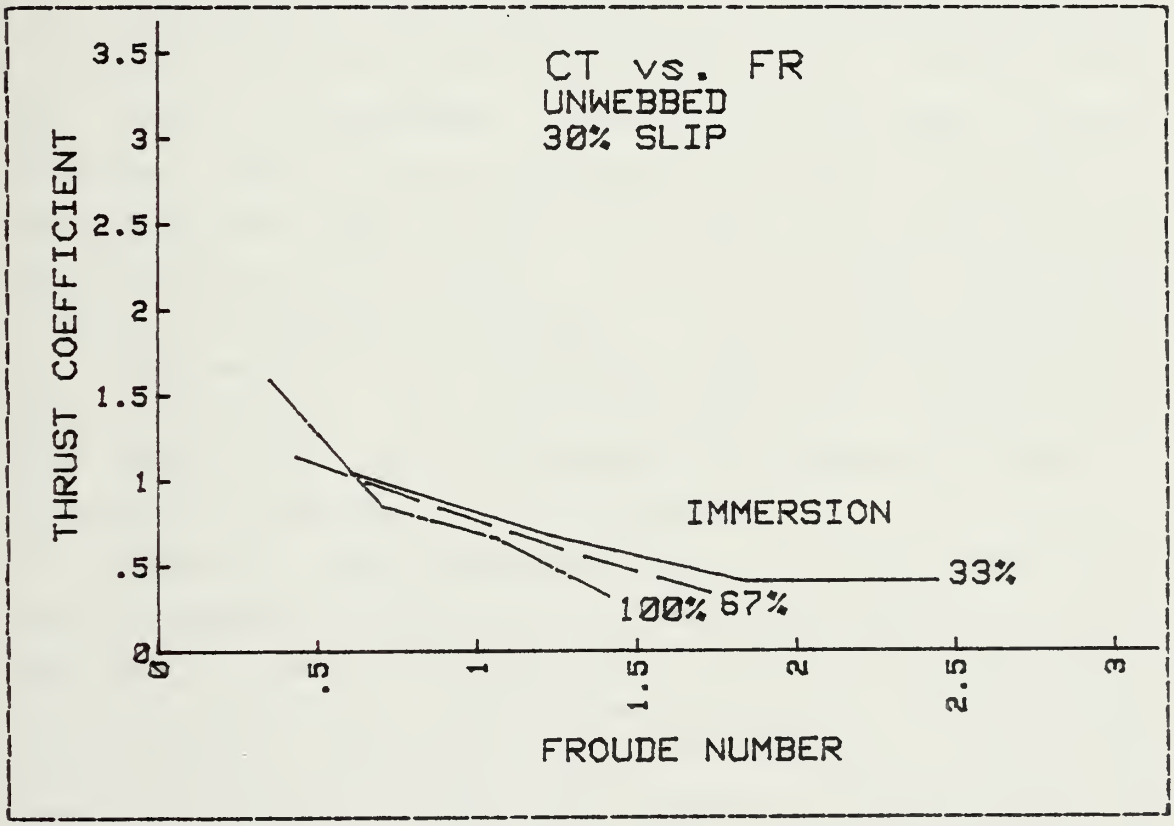


Figure 15 Effect of Speed on Thrust Coefficient.

buildup phenomenon could not offset the vortex loss. In all probability the major loss was due to the water pick up on the emerging side of rotation. This carryover represented potential energy required to be supplied by the prime mover and was irrecoverable as thrust.

B. WEBBED CONFIGURATION

The primary advantage anticipated from the application of the web material was a decrease in the losses associated with the entrainment and carryover of water in the inter-blade cavities at water exit. Other factors, however, could certainly be expected to affect system performance. Among these were the effect of air entrained in the cavities (web cavities in this case) and a limit to the effective contact area, imposed in this case not by the total blade height, but by the available web concave deflection. Further variable was the independent control of the wheel internal pressure. This in turn affected the webbing deflection at water entry and exit, as well as during the thrust-producing immersed phase of operation, where performance was altered by adding the webbing material. The propulsor performance was observed and its variation correlated to the above expected effects. To the variables in the unwebbed case, slip, speed, and percent immersion, were added web length or slackness and internal wheel pressure.

Perhaps the most singular effect in the webbed system was the dramatic improvement in thrust production. It was apparent that this was due to the significant reduction in the water carryover on the water exit side of the paddles. As the paddles approached the water surface, the internal pressure tended to inflate the webbing radially outward and thus "pump" the water directly aft. Thus not only was the water not carried up and above the mean waterline, but it was directed aft parallel to the free surface.

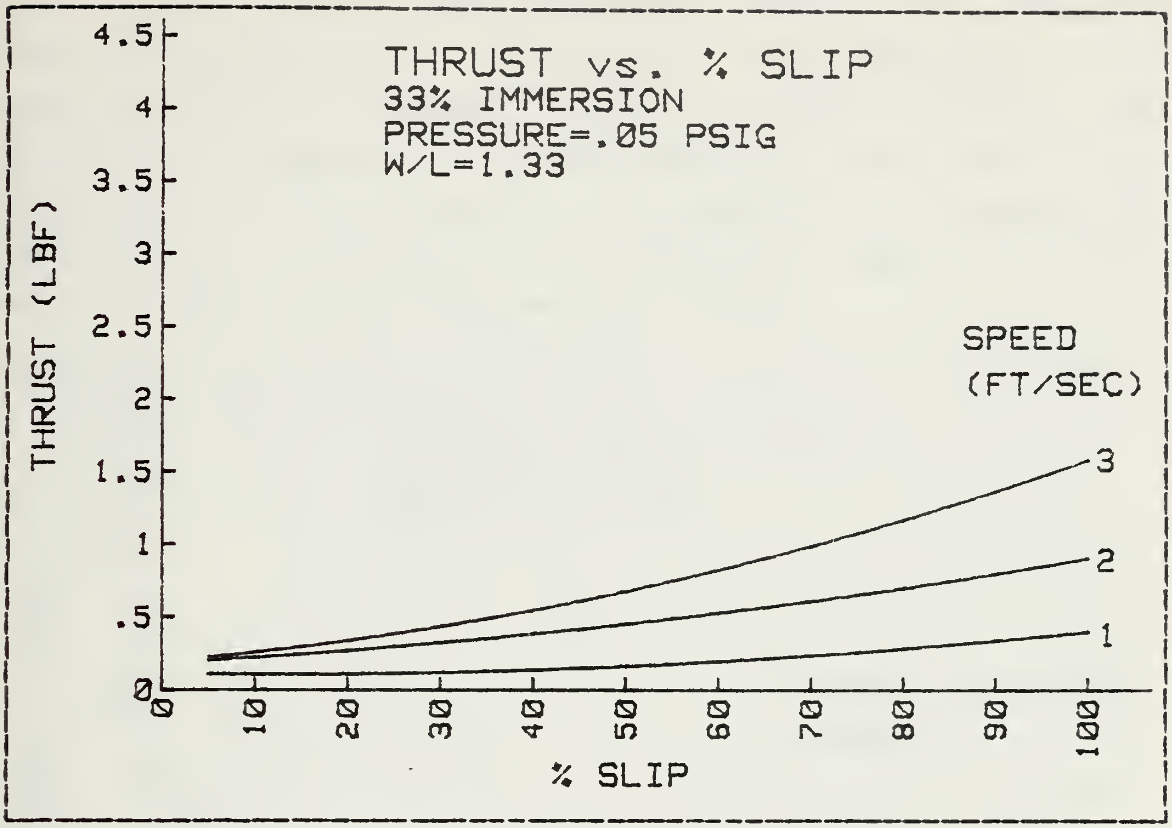


Figure 16 Effect of Speed on Thrust for W/L=1.33.

For the shorter of the two web configurations, W/L=1.33, thrust was seen to increase with forward speed over the entire range tested. Figure 16 illustrates this trend. It was found in most cases, however, that introducing internal pressure to the paddlewheel within the web enclosure degraded the thrust performance of the propulsor. With no applied pressure, the material was seen to fully deflect inward as expected when contacted by the water at entry and to deflect outward as far as the blade tips at water exit. This may have been due to centrifugal forces that acted on the material and the water which wetted the fabric. This continuous inward-outward deflection apparantly introduced some form of pumping mechanism of the trapped internal air

since in all cases a small internal pressure in the range of 0.01 to 0.02 psig was registered. Interestingly, this configuration, no applied internal pressure, was the most effective at augmenting thrust production over that of the baseline unwebbed propulsor. The application of pressure to inflate the web material only detracted from the performance. Figure 17 illustrates this trend.

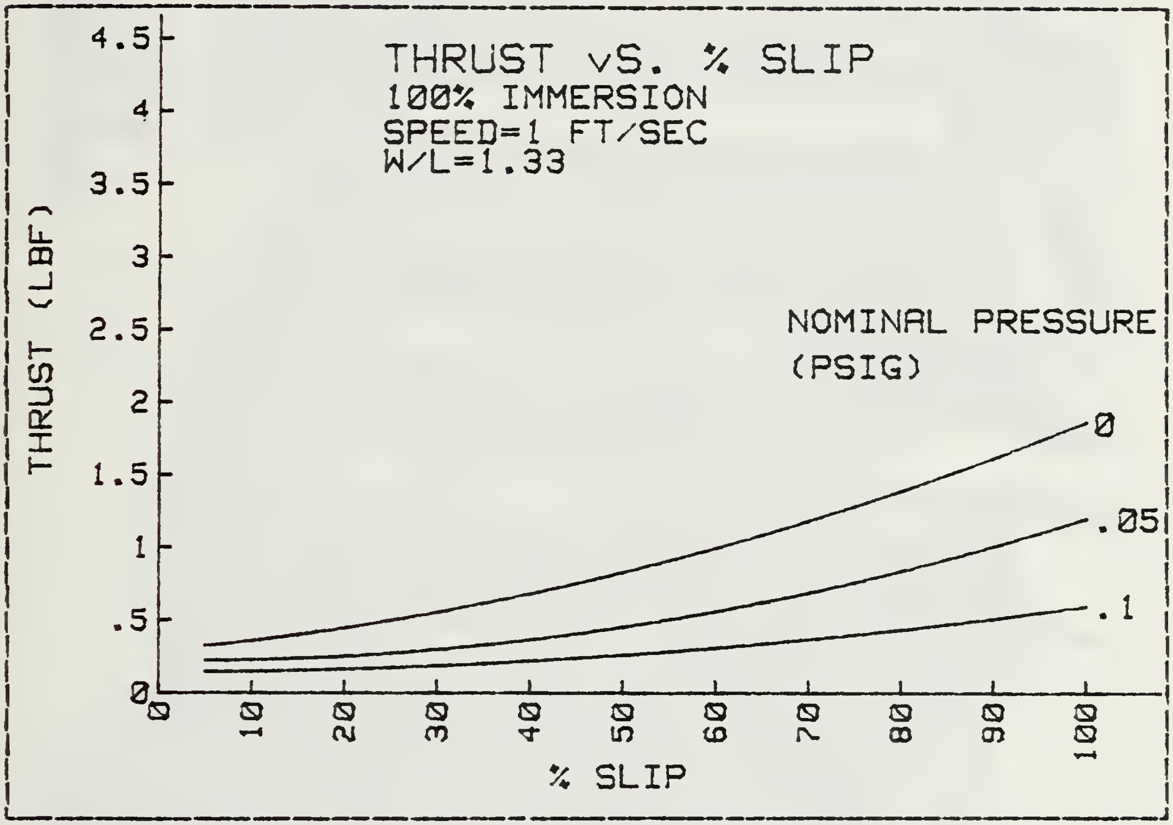


Figure 17 Effect of Internal Pressure on Thrust.

For the longer web material, W/L=2.0, this same self-generated internal pressure was observed with no internal pressure applied and again this provided the optimum performance. Generated thrust dropped off as internal pressure was increased. Comparison between the two web lengths revealed that the longer web material proved superior. An average

improvement in thrust generation of about 90% was seen when W/L was increased from 1.33 to 2.00.

The decrease in thrust with increasing pressure can be related to several effects. First, the ideal case to eliminate water pickup or carryover would be a web/length ratio of W/L=1, or stretching the material from blade tip to blade

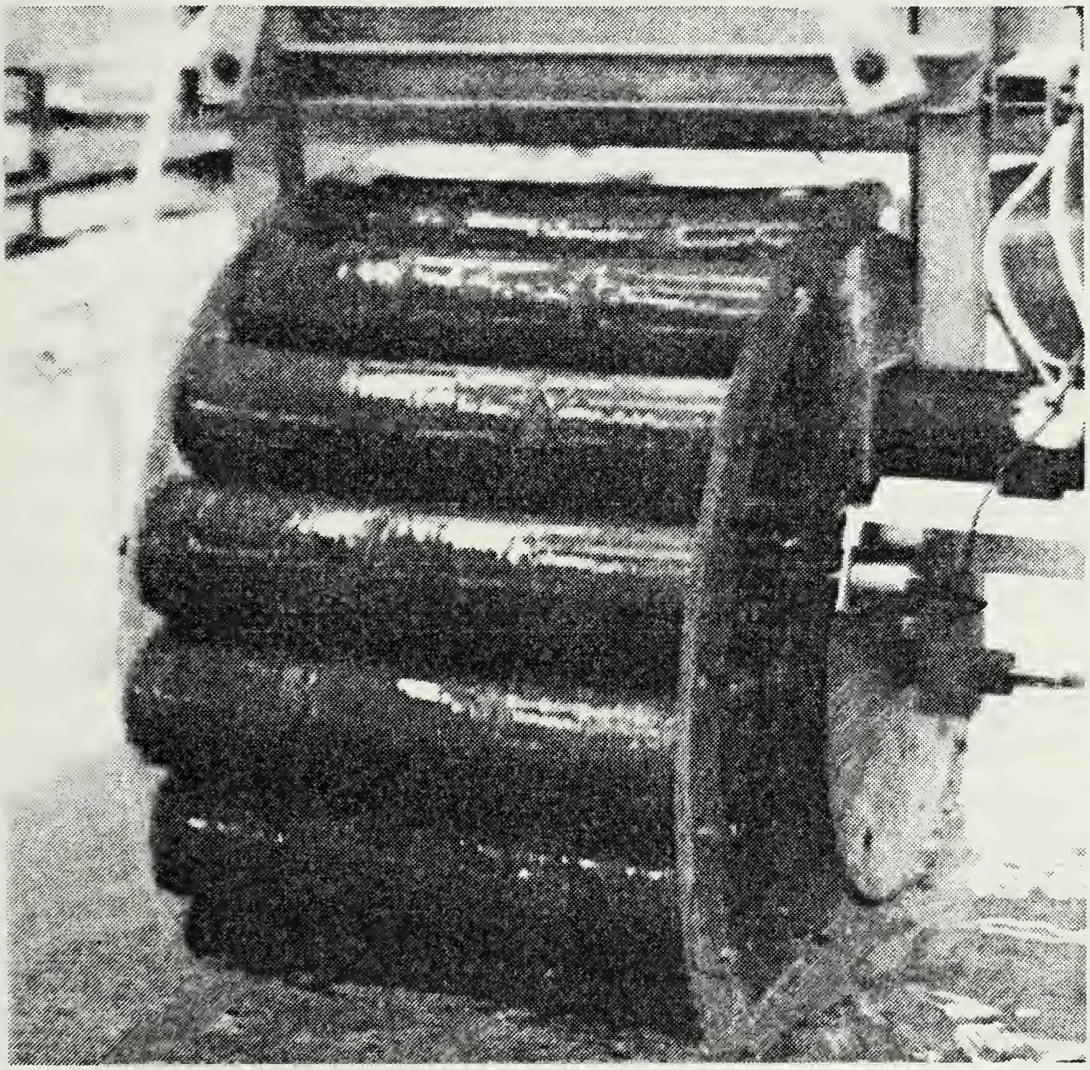


Figure 18 Web Material with 0.1 Psig Internal Pressure.

tip. This, however, would prevent immersion of the blade proper and eliminate blade "purchase" on the water. This

case is obviously of no practical value since material must be available to deflect inward during contact with the water. During this portion of operation the desirable web material should be as long as possible to provide the maximum blade-water contact area. With a web/length ratio in excess of unity, W/L>1, and applied internal pressure, the material assumed the shape of convex lobes during departure from the water surface. With this geometry the inter-lobe apexes served to trap and carry over water. This effect is illustrated in Figure 18 . Entrainment of water was seen to increase with increasing pressure, but even at the highest pressure tested entrainment did not exceed that of the unwebbed case.

With web/length ratio greater than unity, W/L>1, and no applied internal pressure, a different situation was observed. On surface exit the slack excess material simply folded over the leading edge of the following blade. This effectively stripped the interblade water and significantly decreased blade pickup and carryover. Figure 19 is an example of the clean exit geometry found in the case of no applied internal pressure.

The internal pressure also affected the blade-water interaction phenomenon. Obviously, the wave buildup on the pressure face of the blade observed in the unwebbed case was altered by attachment of the webbing material. In this case no water could "spill over the top". For a given web/length ratio and at low immersion levels, the effect was essentially unchanged with respect to the unwebbed case provided no pressure was applied. The material was slack enough and free to deform under the influence of the blade wave. However, once the blade was immersed sufficiently to allow full web tensioning under the influence of dynamic pressure, the web simply remained fully deflected inward throughout its immersed travel.

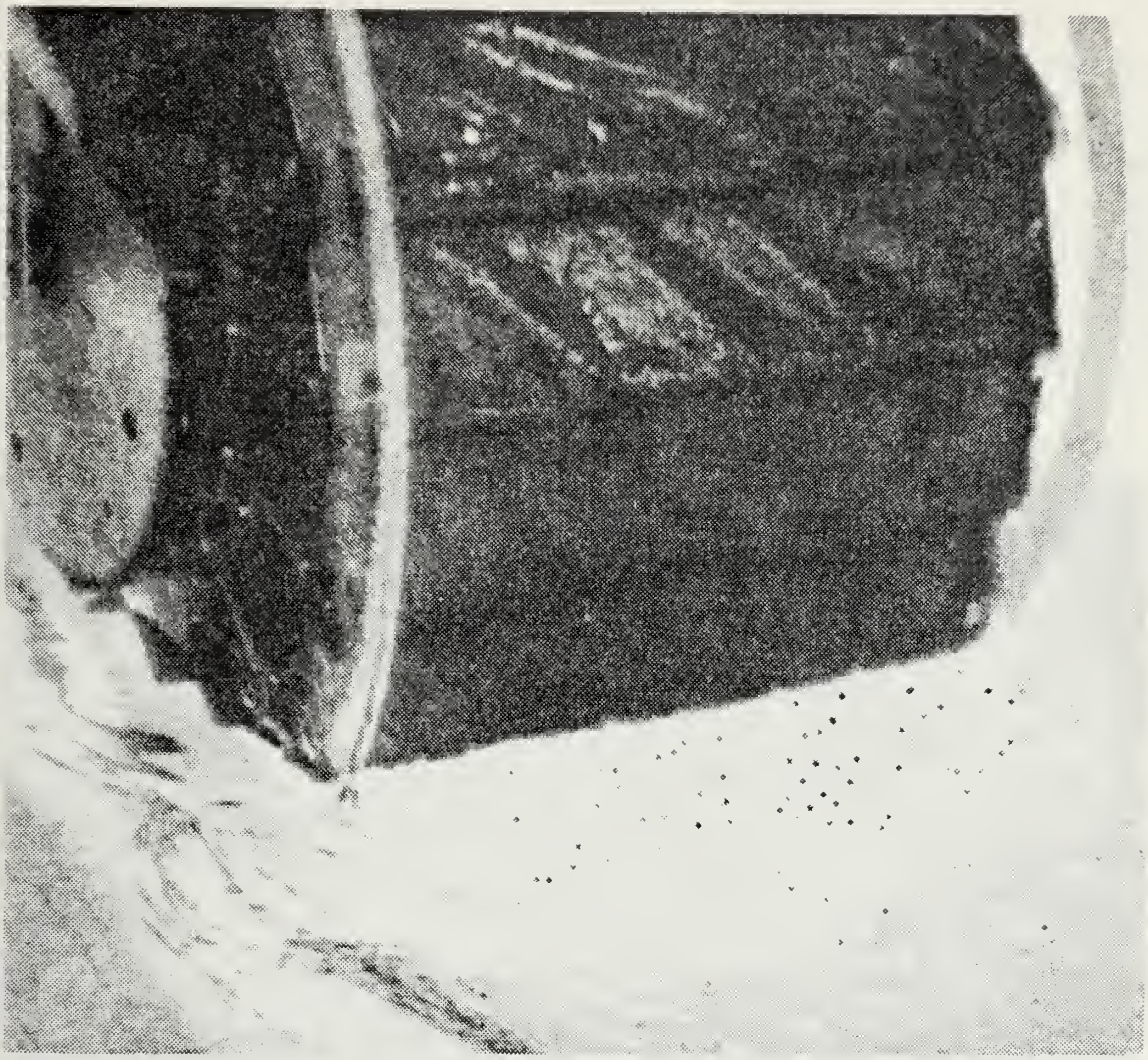


Figure 19   Web Material with No Applied Pressure.

It can be argued that some new maximum effective area was created by the attachment of the web. It is clear that this effective area was significantly greater for the longer web than the shorter one. It appears that with W/L=2.0 the maximum effective area was about equal to that for the unwebbed configuration and less for W/L=1.33. Trends in the thrust data support this observation. The longer web material performed much better than the shorter in the

operating regime where the maximum effective area would be a governing consideration, i.e. at 67% to 100% immersion.

Applied internal wheel pressure controlled the inward deflection of the webbing. The shape of the webbing, concave or convex, while in the immersed zone, was controlled by a balance between internal pressure forces and external hydrodynamic forces. If internal pressure exceeded hydrodynamic pressure then the membrane assumed a convex geometry. A concave configuration was developed when hydrodynamic forces exceeded internal pressure forces.

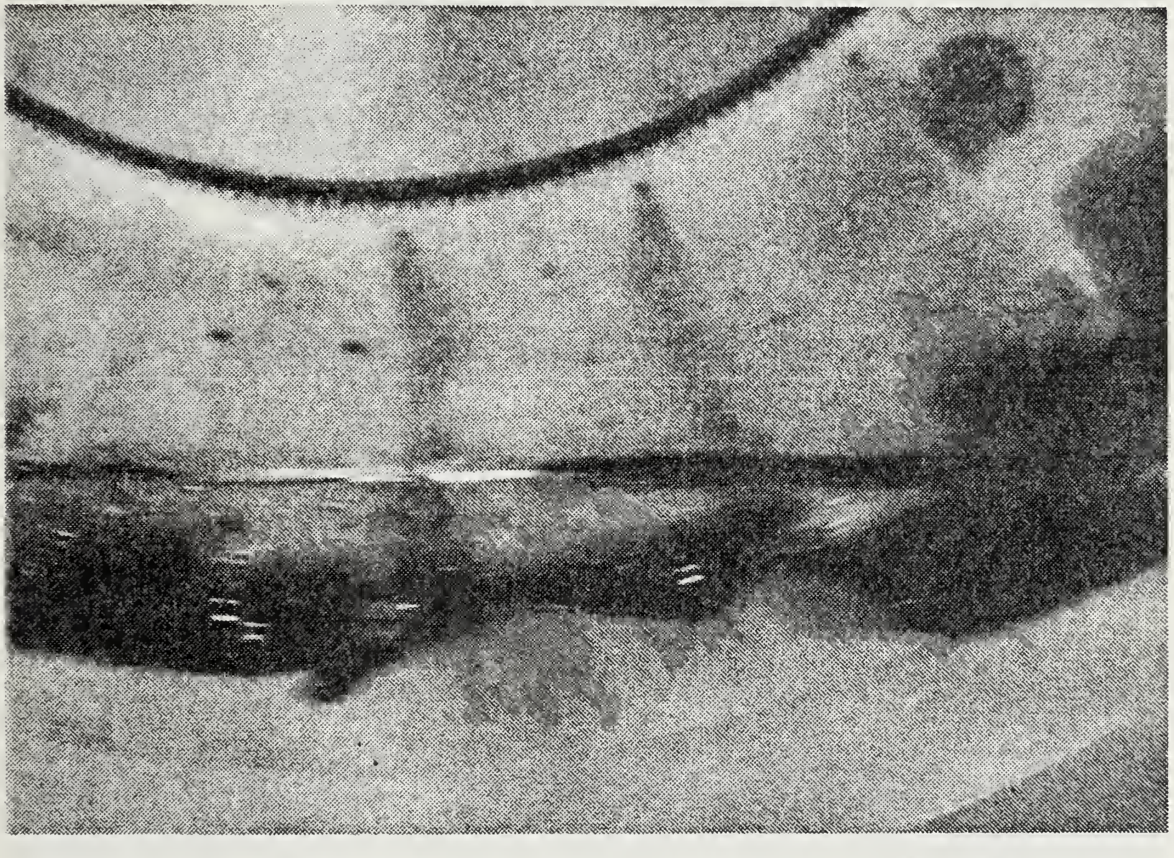


Figure 20 Web Deflection at .05 psi and 33% Immersion.

Examination of Figures 20 and 21 reveals the detrimental interaction when these two forces were in near equilibrium. As the internal wheel pressure approached the local

hydrodynamic pressure the web was prevented from assuming a fully deployed concave orientation. In Figure 20 it can be seen that little inward deflection was allowed and that the web was fully deflected outward even before it began to exit the water. In this case it is obvious that the applied pressure was well beyond the optimum. The effective contact

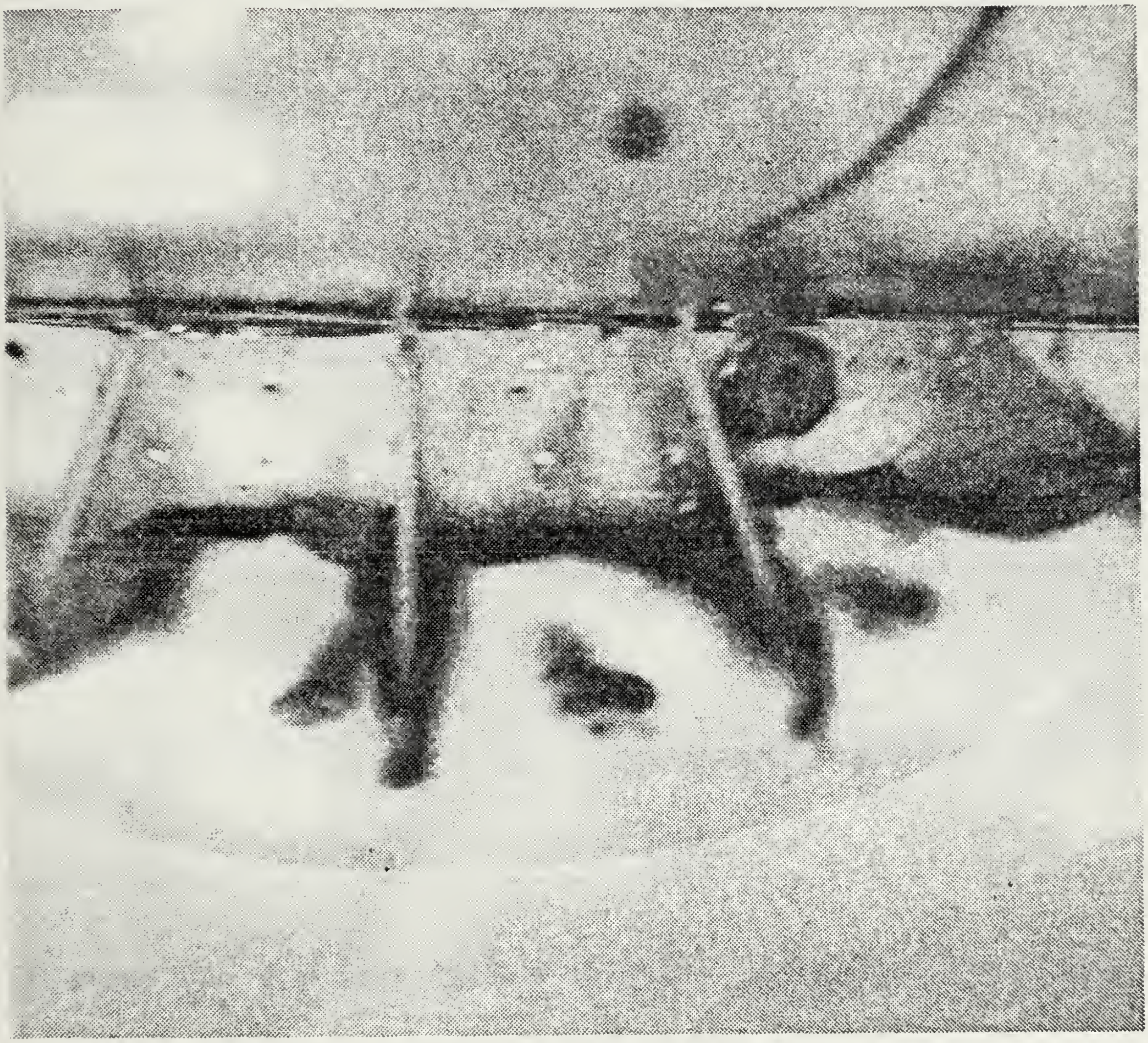


Figure 21 Web Deflection at .05 psi and 100% Immersion.

area was severely reduced. Figure 21 illustrates a closer but still not ideal matching between the wheel and

hydrodynamic pressures. It was observed that the web material was still not fully deflected inward. Also noteworthy in Figure 21 is the fact that the material began to deflect outward at the right of the photo as it approached water exit. This characteristic deflection shape apparently helped to minimize the entrainment of water. A comparison of generated thrust for these two configurations is shown in Figure 22 .

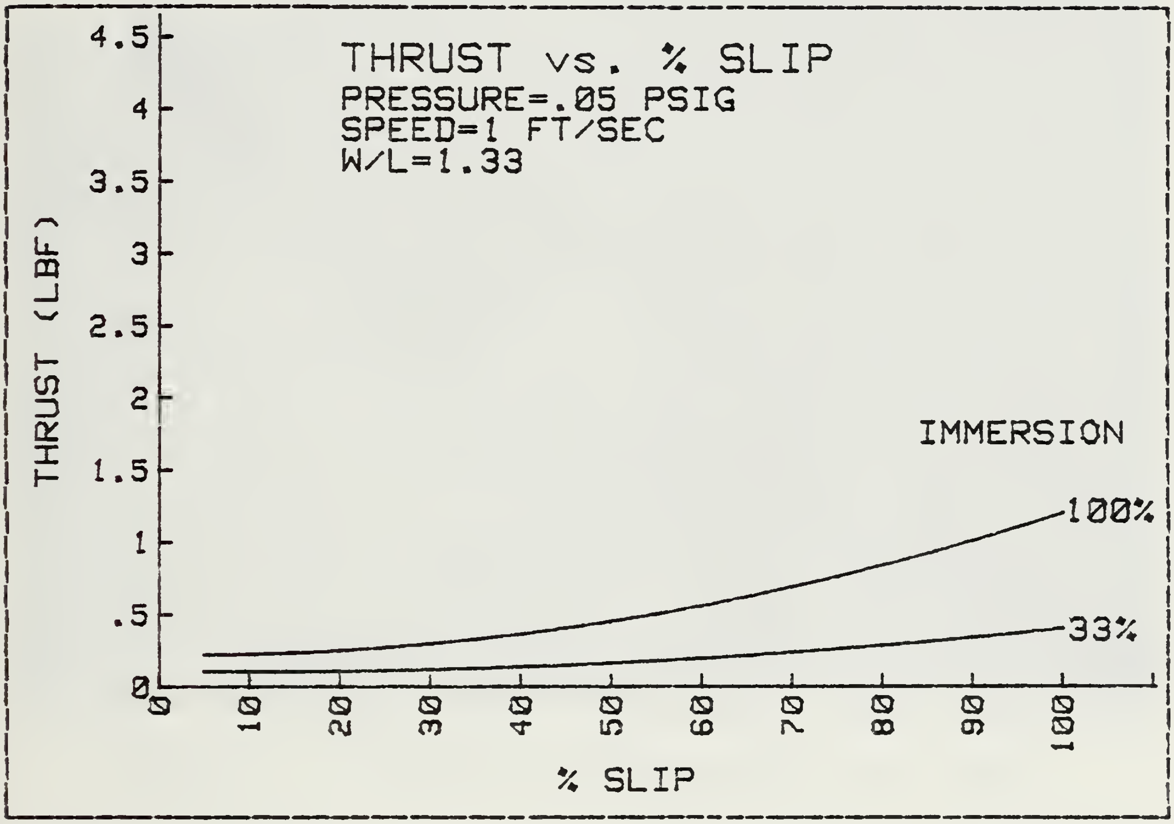


Figure 22 Pressure Effect Relative to Percent Immersion.

The interblade webbing also appeared to improve conditions in the blade entry phase. The web prevented formation of an atmospheric entry cavity on the suction face of the paddle. The web appeared to "control" the filling of the suction cavity and allowed a more gradual acceleration of

the local flow field. Figure 23 illustrates the membrane geometry during the blade entry phase. The true significance of this effect is evident by comparing entrainment for the unwebbed case (Figure 14) and for the webbed geometry (Figure 21).

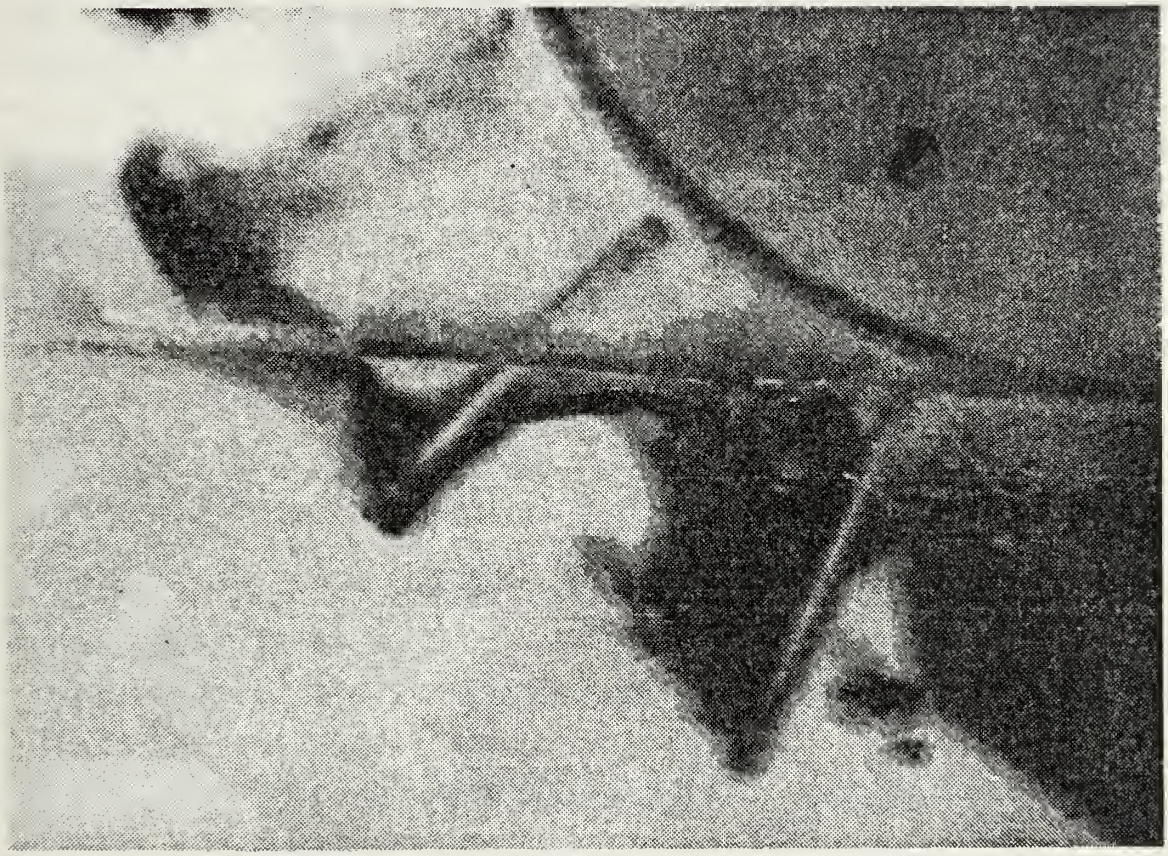


Figure 23 Reduced Air Entrainment Due to Web.

V. CONCLUSIONS

A series of useful comparison curves of the 39 configurations studied is provided in Appendix E. These show many of the relationships among the system variables discussed. They are presented in terms of thrust coefficient versus percent slip over a variety of parameter variations. Study of these curves together with visually observed phenomena led to several key conclusions regarding the enhanced performance of a webbed or enclosed paddlewheel propulsor vs. that of a conventional paddlewheel.

(1) Applying a web material from blade tip to blade tip of a paddlewheel propulsor greatly enhanced the thrust production of the unit. This was primarily due to the significant reduction of carryover water. The benefit was an increase in the rearward momentum change imparted to the liquid. Increases of over 600% in the thrust coefficient were obtained in the best cases, and some improvement was indicated over the entire range of speed and percent blade immersion studied.

(2) The ratio of web material length to blade tip spacing, W/L, was an important parameter. In the two cases examined, thrust generation was increased significantly with an increase in W/L. An average improvement of 90% was realized for a 50% increase in W/L. It is possible that a very large W/L ratio would allow full advantage to be taken of existing bare blade depth or even a possible extension of the effective blade contact area beyond that afforded by the actual blade. In the limit it may be attractive to eliminate the blades proper and to stretch web material between tension cables.

(3) Internal system pressure was a critical parameter. In the case of the small hydrostatic/hydrodynamic pressures encountered in this system, the small internally generated pressure due to centrifugal forces was sufficient to provide the required deflection. This was true even at the highest speeds and at 100% blade immersion. Increased pressures beyond this range served as a detriment to the production of thrust. The blade material was not able to fully deflect inward in order to take full advantage of available contact area in the immersed zone. In the out-of-water zone high air pressure caused convex web geometries and increased water carryover. A matching problem obviously exists and operating pressures must be chosen to fit the system design relative to speed and total blade immersion depth.

It is apparent that the introduction of webbing material on a paddlewheel system exhibits significant performance improvements. The interrelationships of the various parameters need to be explored further and detailed modelling studies should be undertaken.

VI. RECOMMENDATIONS

It is recommended that further research into the applicability of a webbed paddlewheel propulsor to existing transportation requirements be conducted. Some areas of primary concern are the following:

(1) Accurate modelling of system parameters and material/water properties should be done to better assess the magnitude of importance of the effects observed. The modelling of the material stiffness is the key element.

(2) Attempts to quantify the advantages and disadvantages offered by the available variations in system parameters should be made and operating envelopes for vehicle speed, size, and propulsor power should be developed in order to determine more precisely what applications may prove promising.

(3) Eventual design, fabrication, and testing of full scale prototype propulsors should be accomplished for the applications which prove most promising.

APPENDIX A

TEST EQUIPMENT AND SENSORS

Quantity Measured	Sensor/Equipment	Sensor Accuracy
Velocity, V	CELESCO DV301 Position Velocity Transducer	0.025 %
Pressure, P	MICRO SWITCH 144 PC Pressure Transducer	0.325 %
Thrust, T	KISTLER-MORSE DLC-351-005 Force Gage	0.002 %
RPM	DC Generator	0.059 %
Data Acquisition	HP 3497A Data Acquisition/ Control Unit	.002 %
Data Processing	HP 9826 Computer	
Data Output	HP 2671A Printer	

APPENDIX B

SYSTEM NOMENCLATURE AND CONSTANTS

B	Paddle beam (12 inches)
H	Paddle height (3 inches)
D	Max. static draft of paddle when at rest, inches
R	Effective wheel radius, measured to the midpoint of the immersed portion of the paddle, inches
L	Blade tip to blade tip chord distance (3 inches)
W	Blade to blade web length, inches
RPM	Measured wheel revolutions per minute
U	Average paddle forward velocity calculated at the midpoint of the immersed portion of the paddle, ft/sec
V	Carriage forward speed, ft/sec
% slip	Percent difference in paddle speed and carriage speed % slip = (U-V)/V x 100%
% imm.	Percent of available single paddle depth that is statically immersed % immersion = D/H x 100%
P	Internal wheel pressure with web applied, psig

T Model generated horizontal thrust, lb

ρ Density of water (1.94 lb sec^2 / ft^4)

g Acceleration of gravity (32.2 ft/sec^2)

CT Model thrust coefficient based on static frontally-projected wetted area of a single paddle

$$CT = \frac{2T}{\rho\,(V)^2\,(B \times D/144)}$$

FR Froude number based on paddle immersion (D)

$$FR = \frac{V}{\sqrt{g\,(D/12)}}$$

APPENDIX C

ORIGINAL DATA POINTS

WEB CONFIG. (W/L)	BLADE IMMER. (%)	MODEL SPEED (ft/s)	WHEEL PRESS. (psig)	WHEEL RPM (rpm)	SLIP RATIO (%)	MODEL THRUST (lbf)
unwebbed	33	1.05	--	15.0	0.2	0.016
unwebbed	33	1.11	--	17.3	8.2	0.047
unwebbed	33	1.04	--	17.7	19.1	0.061
unwebbed	33	0.99	--	19.4	36.3	0.121
unwebbed	33	1.04	--	20.6	38.5	0.108
unwebbed	33	1.01	--	25.3	75.1	0.296
unwebbed	33	1.04	--	27.6	85.0	0.454
unwebbed	33	2.05	--	31.4	6.8	0.060
unwebbed	33	2.04	--	34.1	16.5	0.243
unwebbed	33	2.05	--	34.4	16.5	0.063
unwebbed	33	2.06	--	40.9	38.1	0.284
unwebbed	33	2.05	--	41.7	42.1	0.329
unwebbed	33	2.02	--	42.1	45.4	0.324
unwebbed	33	2.05	--	49.5	68.8	0.554
unwebbed	33	2.09	--	52.8	75.7	0.722
unwebbed	33	2.00	--	52.9	84.5	0.714
unwebbed	33	1.85	--	52.7	99.5	0.858
unwebbed	33	3.04	--	46.4	6.3	0.097
unwebbed	33	3.02	--	52.9	22.2	0.272
unwebbed	33	3.11	--	59.3	32.8	0.375
unwebbed	33	2.74	--	53.6	36.5	0.321
unwebbed	33	2.85	--	56.8	39.2	0.354
unwebbed	33	3.04	--	66.3	52.3	0.547
unwebbed	33	3.04	--	72.0	65.3	0.614
unwebbed	33	3.11	--	75.4	69.1	0.834
unwebbed	33	3.12	--	79.8	79.8	0.977

unwebbed	33	3.11	--	82.9	85.8	0.987
unwebbed	33	3.13	--	85.4	90.2	1.124
unwebbed	33	3.99	--	61.7	8.10	0.108
unwebbed	33	3.94	--	68.4	21.1	0.331
unwebbed	33	4.00	--	69.6	21.5	0.368
unwebbed	33	3.96	--	69.6	22.8	0.388
unwebbed	33	3.97	--	70.1	23.5	0.368
unwebbed	33	3.91	--	73.9	31.9	0.608
unwebbed	33	3.88	--	78.7	41.7	0.664
unwebbed	33	4.06	--	83.9	44.0	0.885
unwebbed	33	3.65	--	84.3	61.4	0.922
unwebbed	33	4.06	--	99.0	70.0	1.211
unwebbed	33	4.00	--	99.4	73.3	1.517
unwebbed	33	4.02	--	105.2	82.5	1.644
unwebbed	33	4.03	--	109.2	89.0	1.733
unwebbed	33	4.07	--	114.2	96.1	1.888
unwebbed	67	0.98	--	15.0	0.3	0.040
unwebbed	67	0.84	--	15.4	20.4	0.152
unwebbed	67	0.91	--	19.1	38.0	0.234
unwebbed	67	0.93	--	24.4	71.4	0.655
unwebbed	67	0.97	--	27.0	82.1	0.825
unwebbed	67	0.93	--	27.8	95.4	1.089
unwebbed	67	2.23	--	40.1	17.3	0.335
unwebbed	67	2.16	--	40.5	22.6	0.423
unwebbed	67	2.02	--	47.2	52.7	1.018
unwebbed	67	2.04	--	47.7	53.2	1.077
unwebbed	67	2.00	--	55.2	80.6	1.861
unwebbed	67	2.91	--	46.5	4.6	0.248
unwebbed	67	2.94	--	50.5	12.3	0.365
unwebbed	67	2.92	--	63.2	41.7	1.135
unwebbed	67	2.92	--	65.7	47.4	1.283
unwebbed	67	2.96	--	72.4	59.9	1.726
unwebbed	67	2.97	--	73.0	61.0	1.817
unwebbed	67	2.93	--	83.2	86.4	2.587
unwebbed	67	3.92	--	62.8	4.87	0.118

unwebbed	67	3.85	--	70.7	20.2	0.738
unwebbed	67	3.92	--	75.1	25.3	0.926
unwebbed	67	3.88	--	80.9	36.3	0.973
unwebbed	67	4.04	--	91.1	47.4	1.224
unwebbed	67	3.88	--	107.2	80.9	2.599
unwebbed	100	0.89	--	15.7	8.2	0.136
unwebbed	100	0.91	--	18.0	20.6	0.370
unwebbed	100	0.91	--	18.0	21.6	0.366
unwebbed	100	0.90	--	18.6	26.6	0.365
unwebbed	100	0.94	--	21.0	37.1	0.526
unwebbed	100	0.90	--	20.8	41.6	0.547
unwebbed	100	0.90	--	21.9	49.2	0.617
unwebbed	100	0.93	--	23.0	50.8	0.608
unwebbed	100	0.91	--	23.7	58.2	0.801
unwebbed	100	0.95	--	26.6	70.8	0.933
unwebbed	100	0.94	--	28.0	81.6	1.186
unwebbed	100	0.97	--	29.9	88.4	1.383
unwebbed	100	2.07	--	35.0	3.27	0.207
unwebbed	100	2.20	--	40.8	12.2	0.326
unwebbed	100	2.13	--	44.1	26.2	0.783
unwebbed	100	2.16	--	45.4	27.8	0.773
unwebbed	100	2.10	--	54.1	57.3	1.637
unwebbed	100	2.04	--	53.7	60.6	1.673
unwebbed	100	2.09	--	55.2	61.6	1.616
unwebbed	100	2.06	--	55.3	63.4	1.844
unwebbed	100	2.09	--	56.2	64.0	1.841
unwebbed	100	2.07	--	65.8	93.7	2.881
unwebbed	100	3.14	--	54.3	5.4	0.365
unwebbed	100	3.12	--	59.0	15.2	0.650
unwebbed	100	3.08	--	62.5	23.6	1.341
unwebbed	100	3.10	--	64.1	26.3	1.562
unwebbed	100	3.15	--	65.9	27.6	1.660
unwebbed	100	3.08	--	66.9	32.7	2.050
unwebbed	100	3.09	--	67.9	33.8	1.664
unwebbed	100	3.08	--	71.7	42.5	2.050

unwebbed	100	3.08	--	73.1	45.0	2.100
unwebbed	100	3.10	--	86.2	69.7	3.615
unwebbed	100	3.10	--	96.8	90.7	4.436
unwebbed	100	3.97	--	65.2	0.33	0.149
unwebbed	100	3.97	--	65.7	1.24	0.095
unwebbed	100	4.02	--	69.4	5.30	0.402
unwebbed	100	3.97	--	77.3	18.9	0.812
unwebbed	100	4.02	--	78.4	19.1	0.852
unwebbed	100	4.00	--	78.2	19.4	0.863
unwebbed	100	3.92	--	77.3	20.4	0.690
unwebbed	100	3.95	--	79.8	23.4	0.976
unwebbed	100	3.98	--	82.2	26.2	1.170
unwebbed	100	4.06	--	105.2	58.2	2.375
W/L=1.33	33	1.01	.015	15.0	3.63	0.101
W/L=1.33	33	1.03	.015	21.3	44.8	0.350
W/L=1.33	33	1.02	.015	21.4	45.0	0.356
W/L=1.33	33	1.03	.014	29.5	100.0	0.747
W/L=1.33	33	2.16	.017	36.1	16.8	0.144
W/L=1.33	33	2.17	.011	47.1	51.3	0.420
W/L=1.33	33	2.18	.022	55.4	76.9	0.664
W/L=1.33	33	2.17	.014	58.4	87.9	0.833
W/L=1.33	33	3.05	.021	51.0	16.8	0.204
W/L=1.33	33	3.04	.022	51.1	16.9	0.210
W/L=1.33	33	3.04	.022	60.2	38.2	0.375
W/L=1.33	33	3.20	.021	82.0	77.6	0.843
W/L=1.33	33	1.02	.051	17.6	20.1	0.112
W/L=1.33	33	0.99	.046	20.8	47.2	0.163
W/L=1.33	33	0.97	.048	21.7	56.4	0.179
W/L=1.33	33	1.01	.056	23.8	65.4	0.221
W/L=1.33	33	2.16	.055	35.3	13.7	0.177
W/L=1.33	33	2.18	.054	36.8	17.4	0.262
W/L=1.33	33	2.19	.052	44.2	40.5	0.389
W/L=1.33	33	2.17	.060	53.5	71.7	0.635
W/L=1.33	33	3.07	.052	47.5	7.99	0.248
W/L=1.33	33	3.01	.060	52.7	22.2	0.349

W/L=1.33	33	3.00	.056	62.3	44.6	0.633
W/L=1.33	33	3.05	.056	65.1	48.5	0.641
W/L=1.33	100	0.99	.018	23.5	45.5	0.763
W/L=1.33	100	0.98	.017	23.4	46.0	0.774
W/L=1.33	100	1.02	.016	28.1	68.2	1.179
W/L=1.33	100	1.05	.017	33.0	90.8	1.606
W/L=1.33	100	0.94	.058	18.8	22.6	0.268
W/L=1.33	100	1.04	.059	23.6	38.1	0.342
W/L=1.33	100	1.04	.059	28.2	66.4	0.652
W/L=1.33	100	1.00	.060	33.9	100.0	1.231
W/L=1.33	100	1.00	.111	22.1	34.9	0.203
W/L=1.33	100	1.04	.126	23.2	36.0	0.211
W/L=1.33	100	1.01	.125	27.8	63.4	0.329
W/L=1.33	100	0.98	.126	32.1	99.1	0.601
W/L=1.33	100	2.21	.101	40.4	11.3	0.487
W/L=1.33	100	2.23	.109	40.9	11.8	0.503
W/L=1.33	100	2.21	.110	42.0	16.0	0.559
W/L=1.33	100	2.23	.103	48.0	31.8	0.726
W/L=1.33	100	2.20	.104	49.4	37.2	0.759
W/L=1.33	100	2.19	.109	71.7	100.0	1.542
W/L=2.00	33	0.92	.024	14.9	13.8	0.175
W/L=2.00	33	0.95	.024	16.2	18.3	0.209
W/L=2.00	33	0.95	.027	19.9	46.3	0.303
W/L=2.00	33	0.93	.027	22.0	64.6	0.901
W/L=2.00	33	0.88	.026	24.1	91.2	1.089
W/L=2.00	33	0.93	.052	14.8	10.7	0.146
W/L=2.00	33	0.92	.055	17.9	36.3	0.269
W/L=2.00	33	0.89	.055	21.5	69.1	0.631
W/L=2.00	33	0.92	.057	24.9	89.4	0.832
W/L=2.00	33	0.92	.106	16.4	22.0	0.176
W/L=2.00	33	0.88	.108	16.4	31.1	0.192
W/L=2.00	33	0.91	.101	20.5	57.6	0.271
W/L=2.00	33	0.91	.107	21.5	66.1	0.341
W/L=2.00	33	0.92	.107	26.2	98.8	0.513
W/L=2.00	33	2.08	.027	30.0	0.73	0.223

W/L=2.00	33	2.08	.025	31.7	6.25	0.258
W/L=2.00	33	1.93	.026	35.5	28.7	0.466
W/L=2.00	33	1.99	.023	39.7	39.4	0.596
W/L=2.00	33	2.05	.026	51.2	74.0	1.077
W/L=2.00	67	0.93	.027	14.4	0.97	0.499
W/L=2.00	67	0.95	.025	15.6	7.03	0.711
W/L=2.00	67	0.97	.025	17.3	16.6	0.768
W/L=2.00	67	0.95	.024	18.1	24.8	1.001
W/L=2.00	67	0.96	.020	20.5	39.9	1.471
W/L=2.00	67	0.95	.022	22.2	52.9	1.696
W/L=2.00	67	0.99	.022	23.9	58.5	1.961
W/L=2.00	67	0.96	.020	24.9	70.1	2.587
W/L=2.00	67	0.97	.025	26.8	80.1	2.640
W/L=2.00	67	0.98	.025	29.9	99.1	3.108
W/L=2.00	67	0.97	.038	16.4	11.3	0.539
W/L=2.00	67	0.96	.036	19.7	33.5	1.193
W/L=2.00	67	0.95	.031	22.2	52.5	1.588
W/L=2.00	67	1.00	.032	24.2	58.5	1.651
W/L=2.00	67	0.90	.033	25.7	87.9	2.628
W/L=2.00	67	0.92	.065	16.4	17.0	0.502
W/L=2.00	67	0.95	.064	20.5	41.4	0.988
W/L=2.00	67	0.91	.064	22.1	58.6	1.351
W/L=2.00	67	0.94	.065	26.4	84.0	2.028
W/L=2.00	67	0.93	.111	16.0	12.1	0.247
W/L=2.00	67	0.93	.102	16.4	15.1	0.293
W/L=2.00	67	0.93	.114	20.5	43.8	0.548
W/L=2.00	67	0.96	.110	25.3	72.6	0.849
W/L=2.00	67	0.97	.125	28.4	92.3	1.196
W/L=2.00	67	2.20	.020	35.0	4.0	0.510
W/L=2.00	67	2.08	.023	37.0	16.2	0.663
W/L=2.00	67	2.20	.022	40.4	17.0	0.759
W/L=2.00	67	2.05	.019	62.0	97.9	2.973
W/L=2.00	67	2.11	.055	36.4	12.5	0.466
W/L=2.00	67	2.11	.054	45.3	40.3	1.046
W/L=2.00	67	2.11	.052	52.0	61.0	1.687

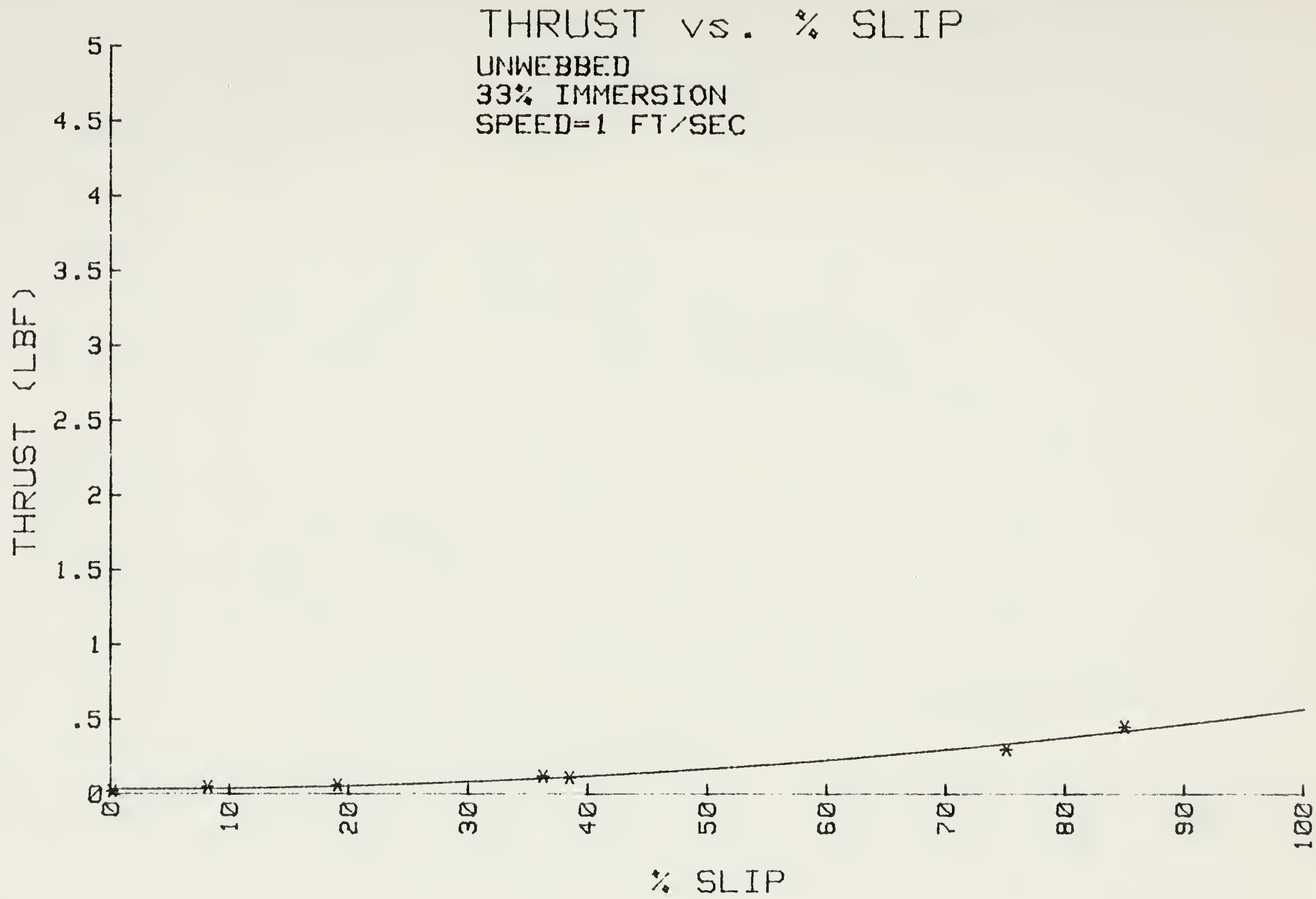
W/L=2.00	67	2.11	.056	59.2	83.4	2.180
W/L=2.00	67	2.14	.111	36.6	12.2	0.204
W/L=2.00	67	2.09	.103	36.7	15.3	0.272
W/L=2.00	67	2.12	.108	46.1	42.2	0.714
W/L=2.00	67	2.11	.100	46.0	42.7	0.710
W/L=2.00	67	2.16	.104	50.8	53.7	1.087
W/L=2.00	67	2.11	.107	53.6	66.1	1.139
W/L=2.00	67	3.10	.104	47.6	6.7	0.128
W/L=2.00	67	3.11	.101	53.7	12.8	0.148
W/L=2.00	67	3.09	.118	73.7	56.1	0.570
W/L=2.00	67	3.05	.122	76.0	62.8	0.731
W/L=2.00	67	3.12	.105	89.0	87.6	1.050
W/L=2.00	67	3.82	.109	61.8	5.8	0.124
W/L=2.00	67	3.83	.106	67.1	14.7	0.134
W/L=2.00	67	3.83	.108	70.6	20.7	0.143
W/L=2.00	67	3.87	.112	78.3	32.5	0.191
W/L=2.00	67	3.84	.109	111.5	90.1	0.487
W/L=2.00	100	0.88	.104	15.8	10.0	0.687
W/L=2.00	100	0.95	.104	20.4	31.5	0.775
W/L=2.00	100	0.94	.105	22.2	45.0	1.045
W/L=2.00	100	0.95	.107	24.0	55.4	1.142
W/L=2.00	100	0.97	.105	25.8	61.8	1.355
W/L=2.00	100	0.95	.105	29.5	89.0	1.537
W/L=2.00	100	2.10	.107	37.8	10.0	0.607
W/L=2.00	100	2.11	.107	40.4	16.6	0.643
W/L=2.00	100	2.07	.108	45.1	31.1	0.713
W/L=2.00	100	2.08	.106	50.0	46.7	0.931
W/L=2.00	100	2.10	.109	53.1	54.6	1.121
W/L=2.00	100	2.10	.109	57.8	68.0	1.204
W/L=2.00	100	2.07	.101	62.4	83.5	1.282
W/L=2.00	100	2.09	.108	64.2	88.0	1.494
W/L=2.00	100	3.01	.120	54.9	11.2	0.465
W/L=2.00	100	3.05	.085	58.1	16.5	0.592
W/L=2.00	100	3.03	.081	59.7	20.4	0.589
W/L=2.00	100	3.02	.089	66.4	34.4	0.741

W/L=2.00	100	3.03	.099	75.3	51.5	0.922
W/L=2.00	100	3.02	.104	84.6	71.2	1.123
W/L=2.00	100	3.00	.101	93.7	90.4	1.375
W/L=2.00	100	3.85	.094	78.8	25.1	0.194
W/L=2.00	100	3.99	.095	88.3	35.1	0.290
W/L=2.00	100	3.85	.110	87.2	38.4	0.277
W/L=2.00	100	3.88	.097	120.7	90.1	0.878

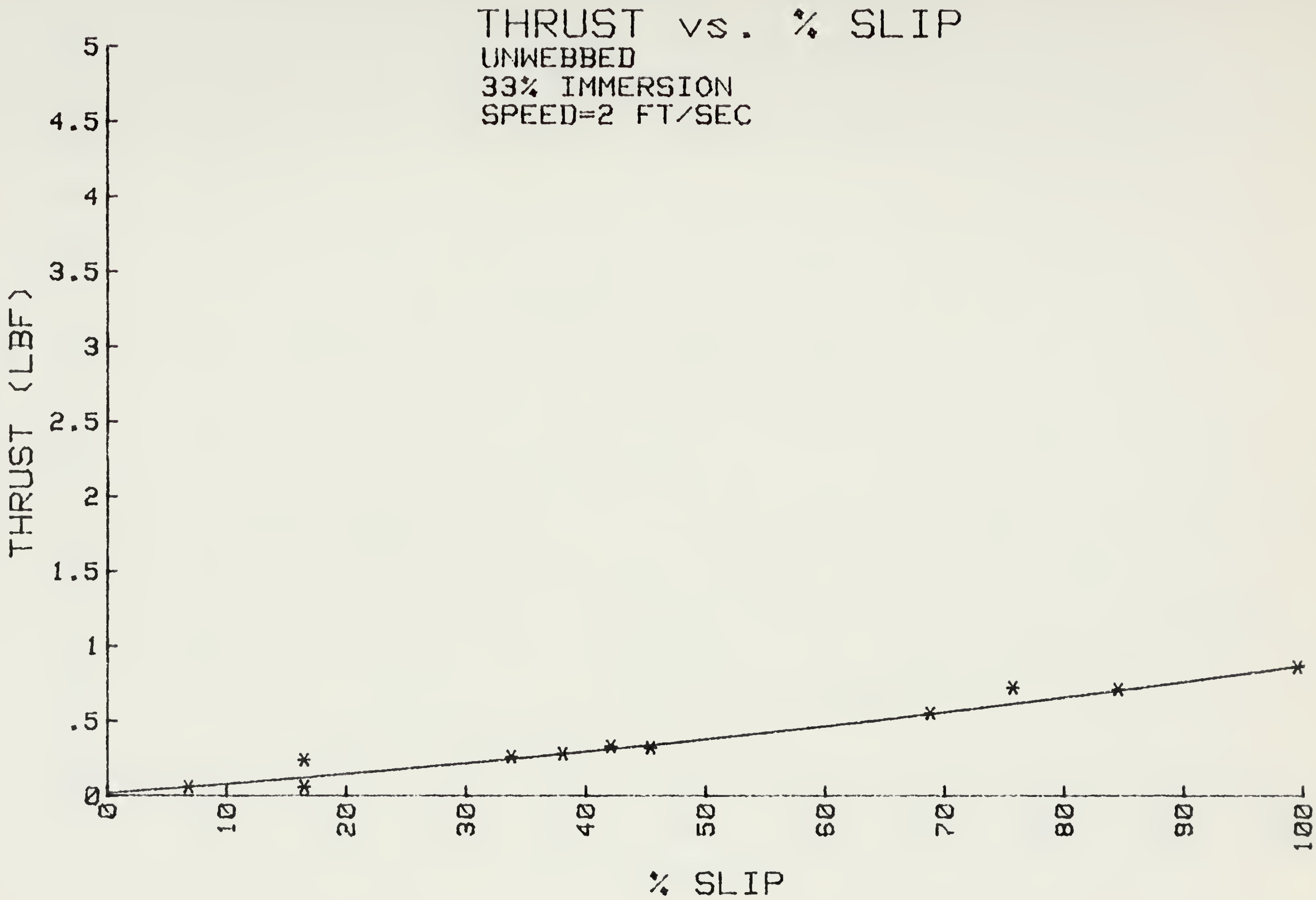
APPENDIX D

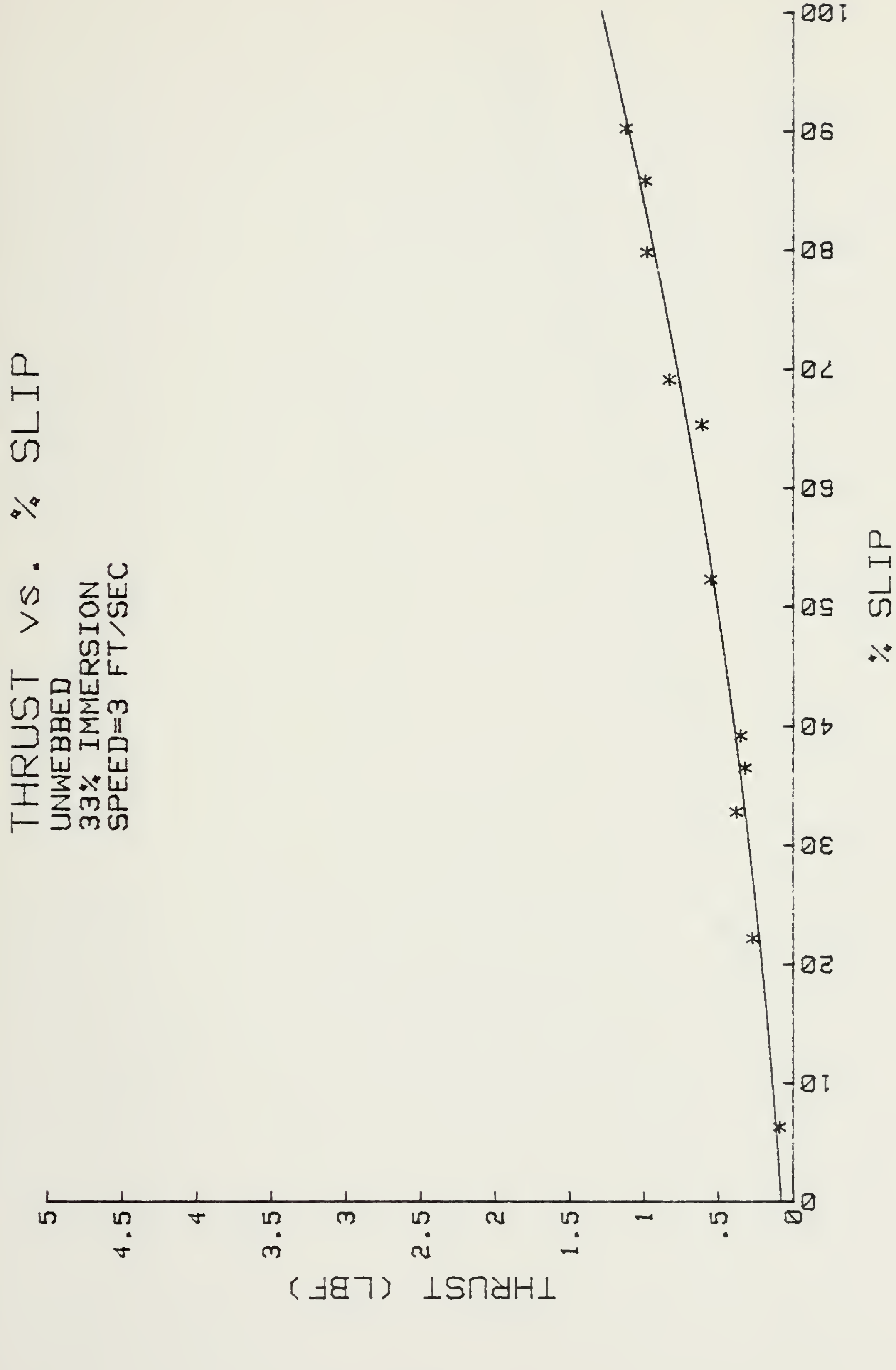
CURVES OF THRUST VS. % SLIP WITH ORIGINAL DATA POINTS

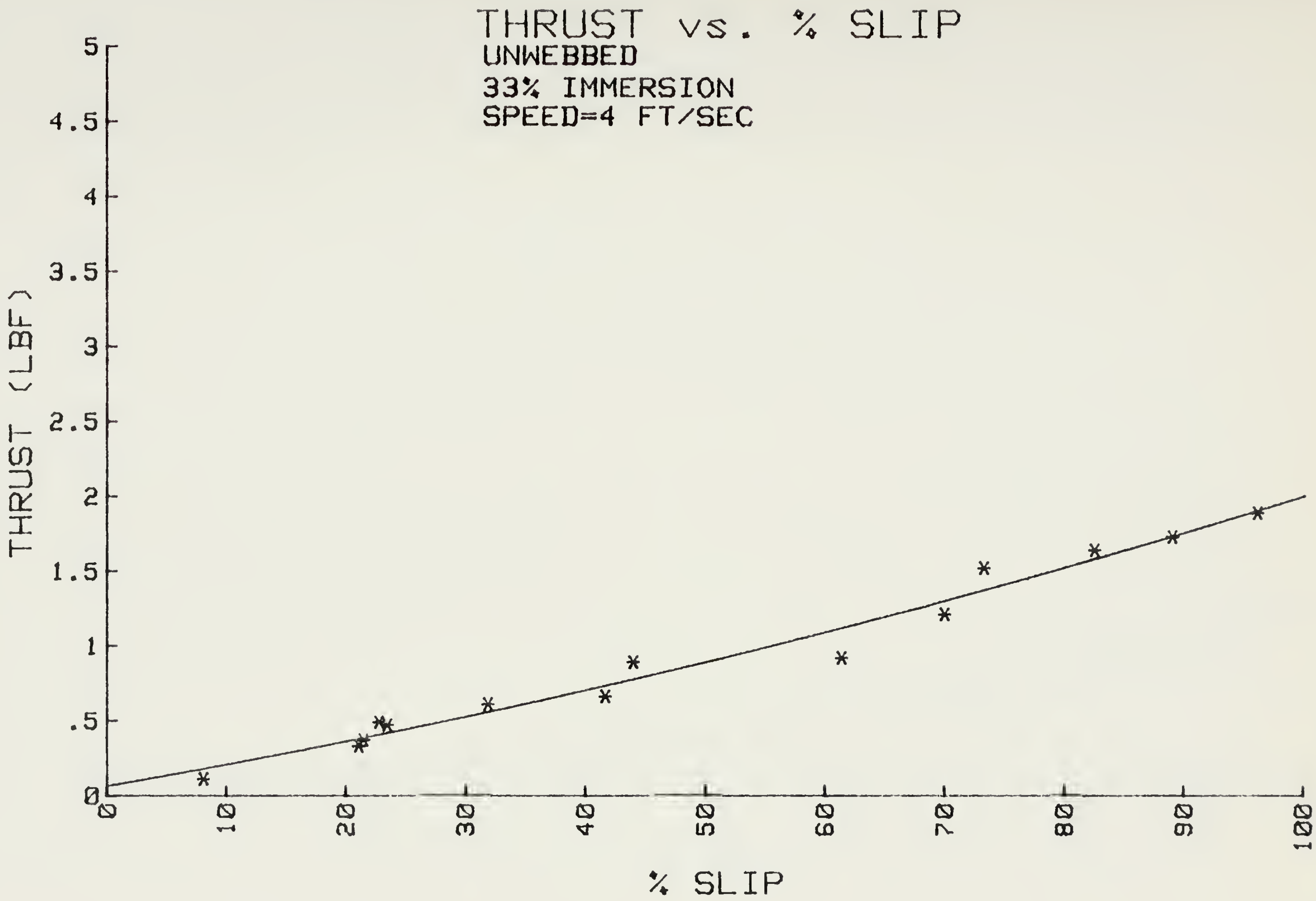
This Appendix contains individual closest fit curves for each of the 39 configurations tested. The curves are presented as THRUST vs. % SLIP. The original data points are superimposed on each curve.

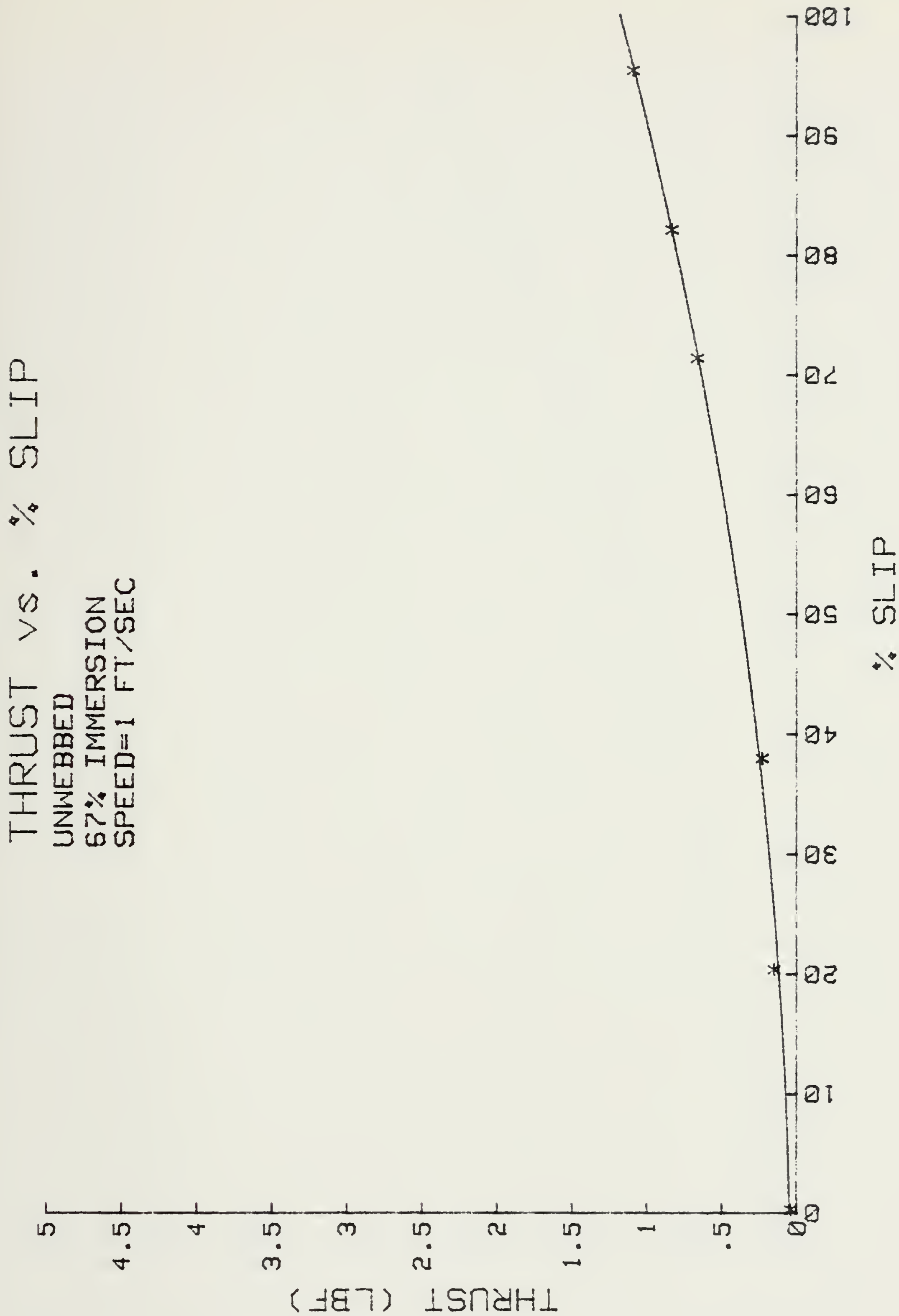


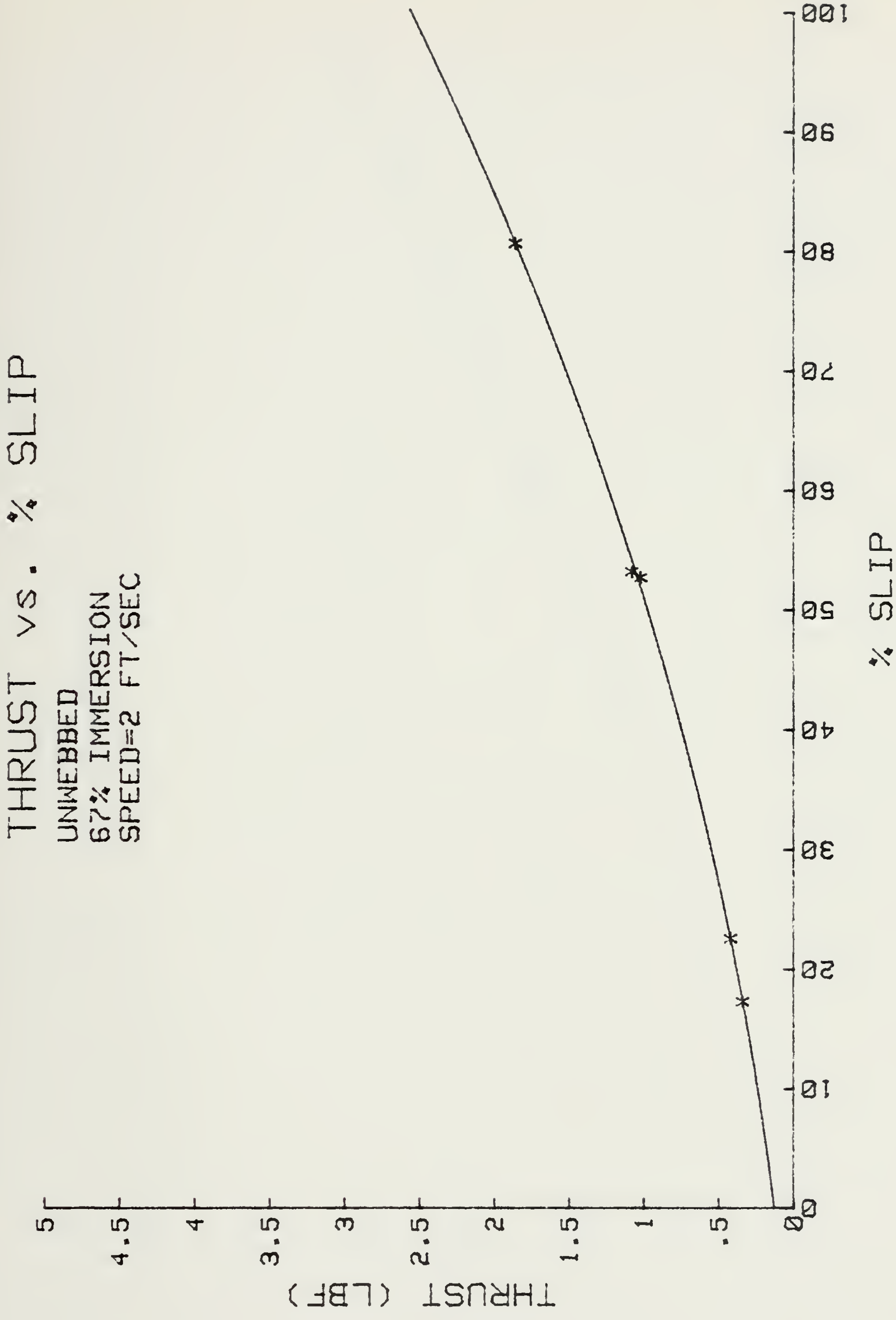
THRUST vs. % SLIP
UNWEBBED
33% IMMERSION
SPEED=1 FT/SEC
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP

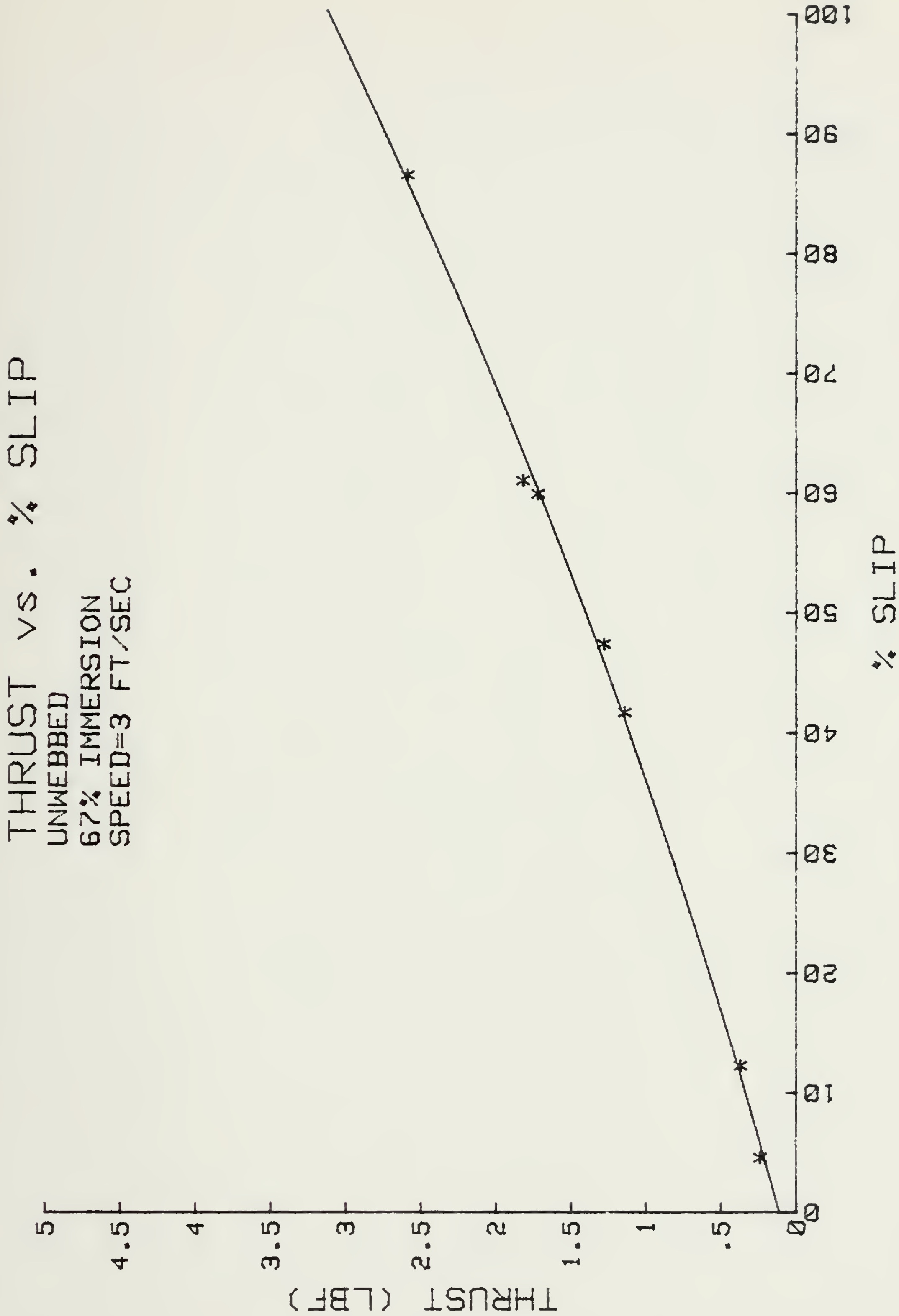

THRUST vs. % SLIP
UNWEBBED
33% IMMERSION
SPEED=2 FT/SEC
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
% SLIP
0
10
20
30
40
50
60
70
80
90
100

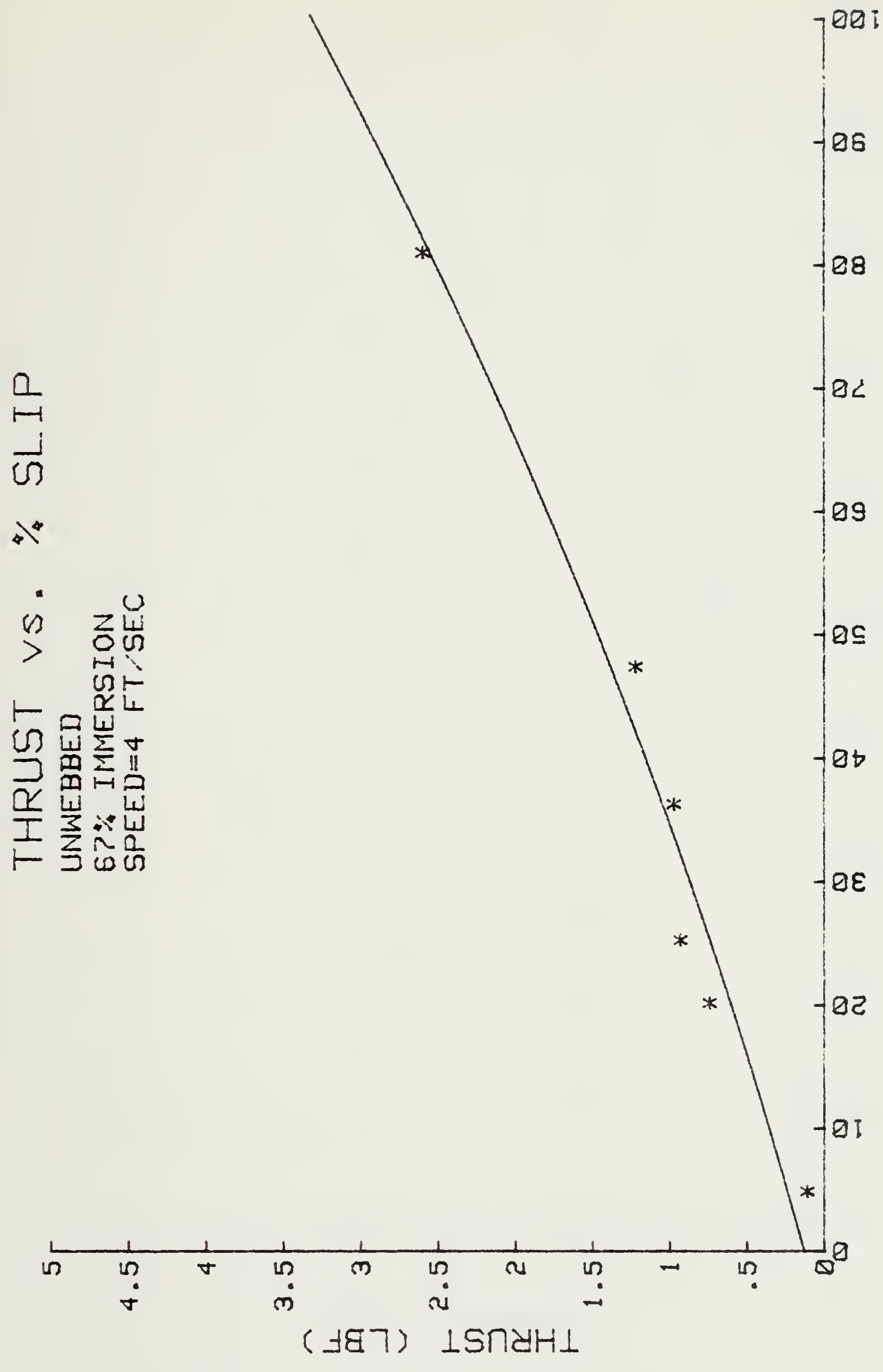

THRUST VS. % SLIP
UNWEBBED
33% IMMERSION
SPEED=3 FT/SEC
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100

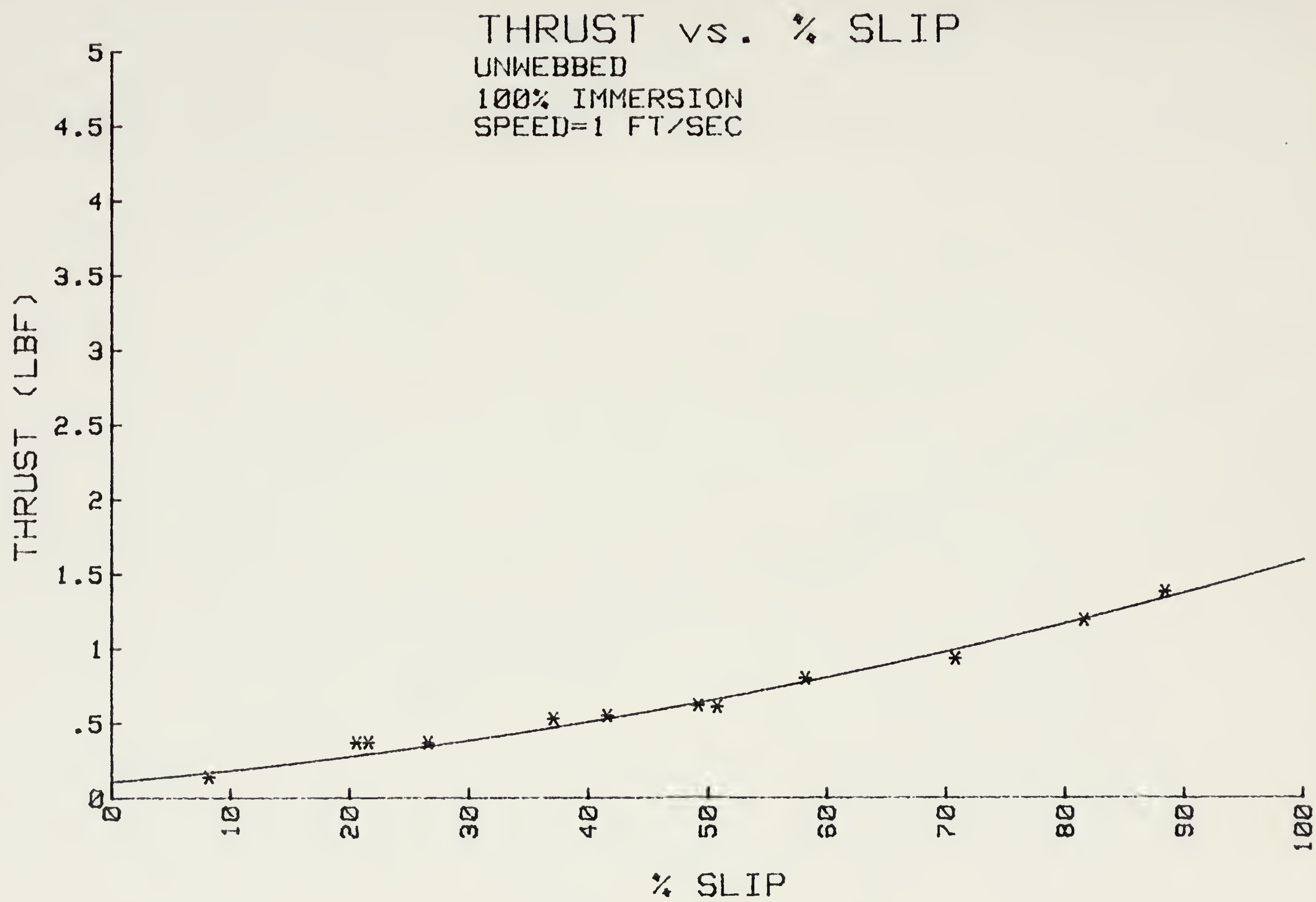

THRUST vs. % SLIP
UNWEBBED
33% IMMERSION
SPEED=4 FT/SEC
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70
80
90
100

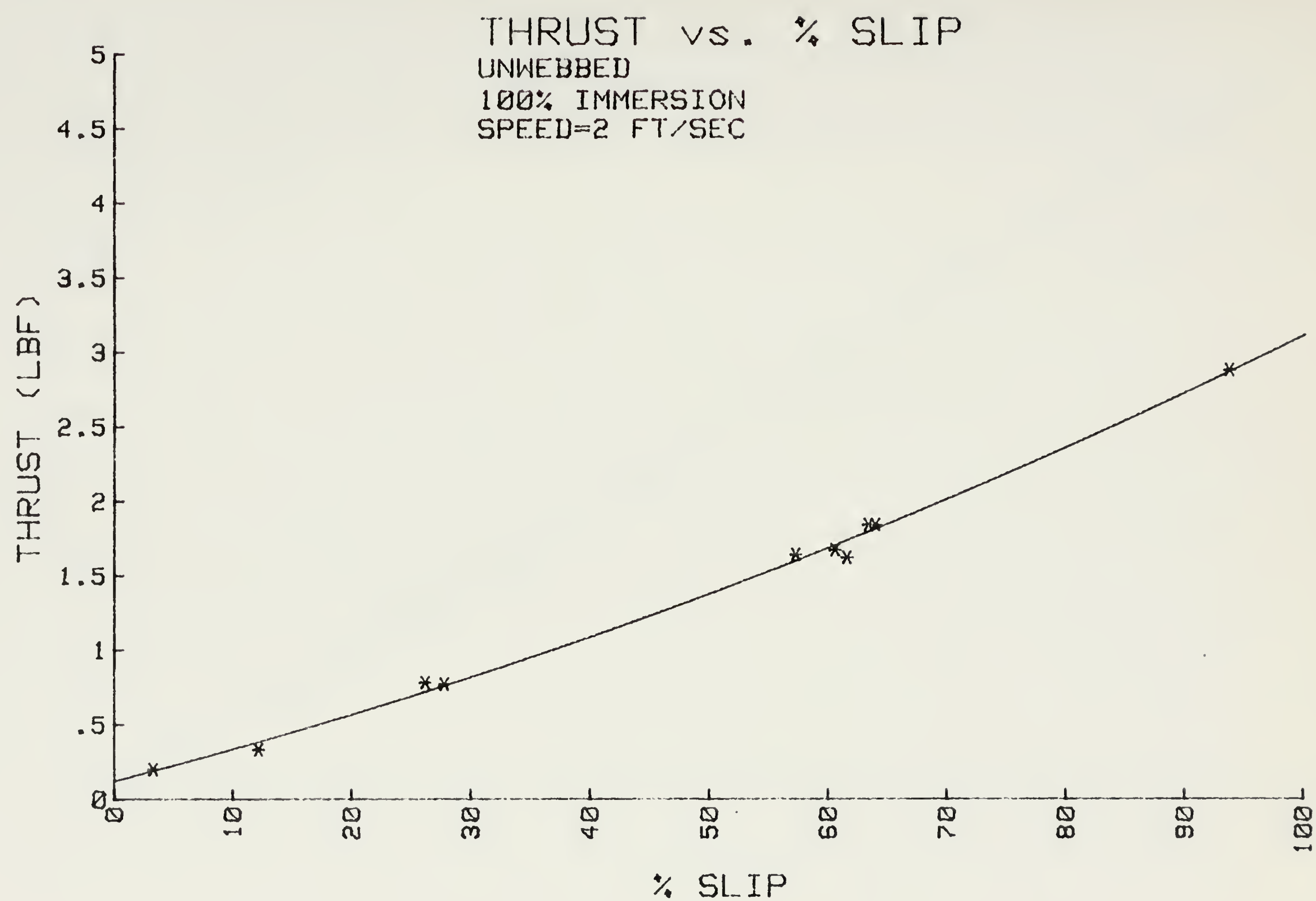

THRUST VS. % SLIP
UNWEBBED
67% IMMERSION
SPEED=1 FT/SEC
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70
80
90
100

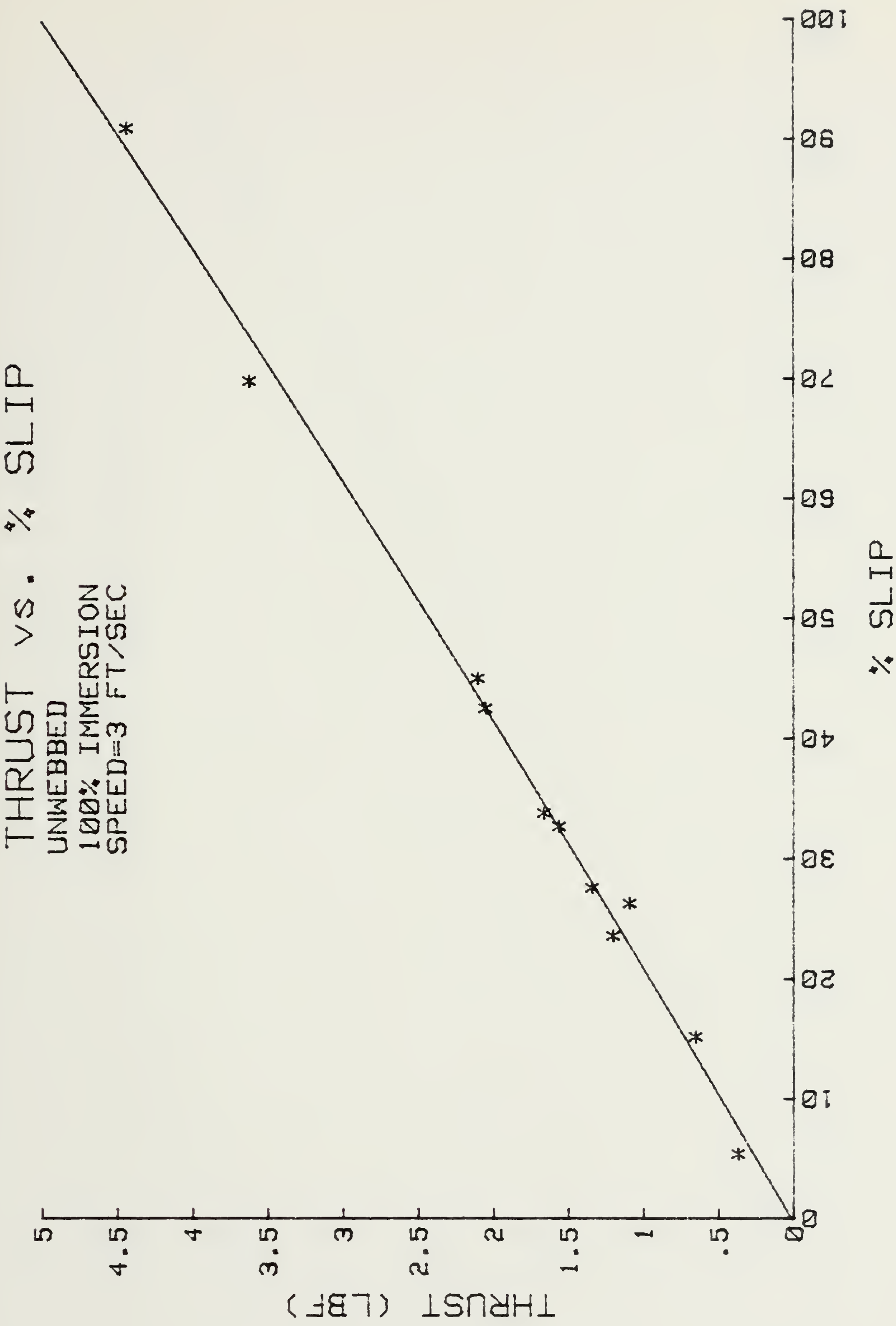

THRUST vs. % SLIP
UNWEBBED
67% IMMERSION
SPEED=2 FT/SEC
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
% SLIP
0
10
20
30
40
50
60
70
80
90
100


THRUST VS. % SLIP
UNWEBBED
67% IMMERSION
SPEED=3 FT/SEC
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70
80
90
100

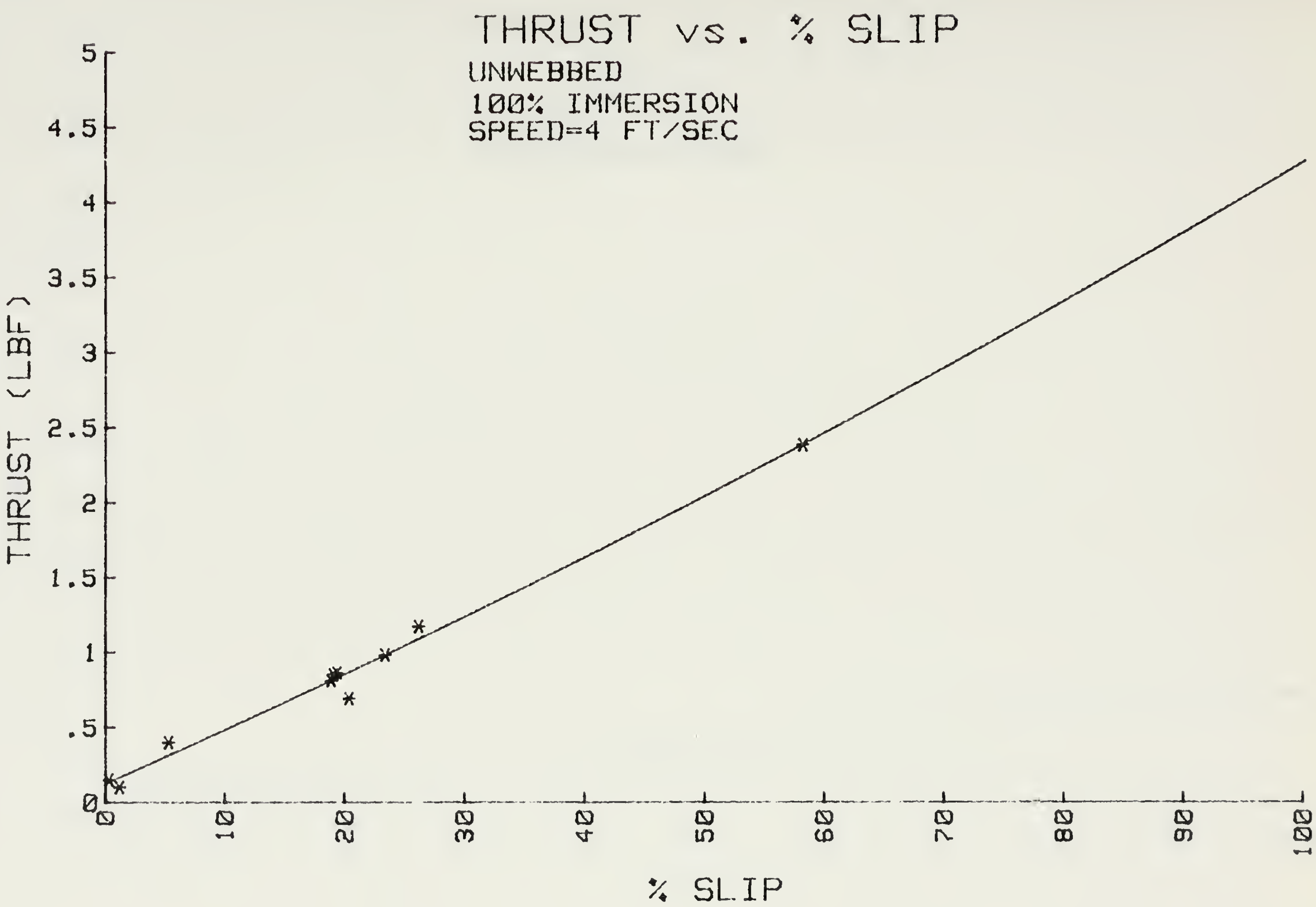

THRUST VS. % SLIP
UNWEBBED
67% IMMERSION
SPEED=4 FT/SEC
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
% SLIP
0
10
20
30
40
50
60
70
80
90
100

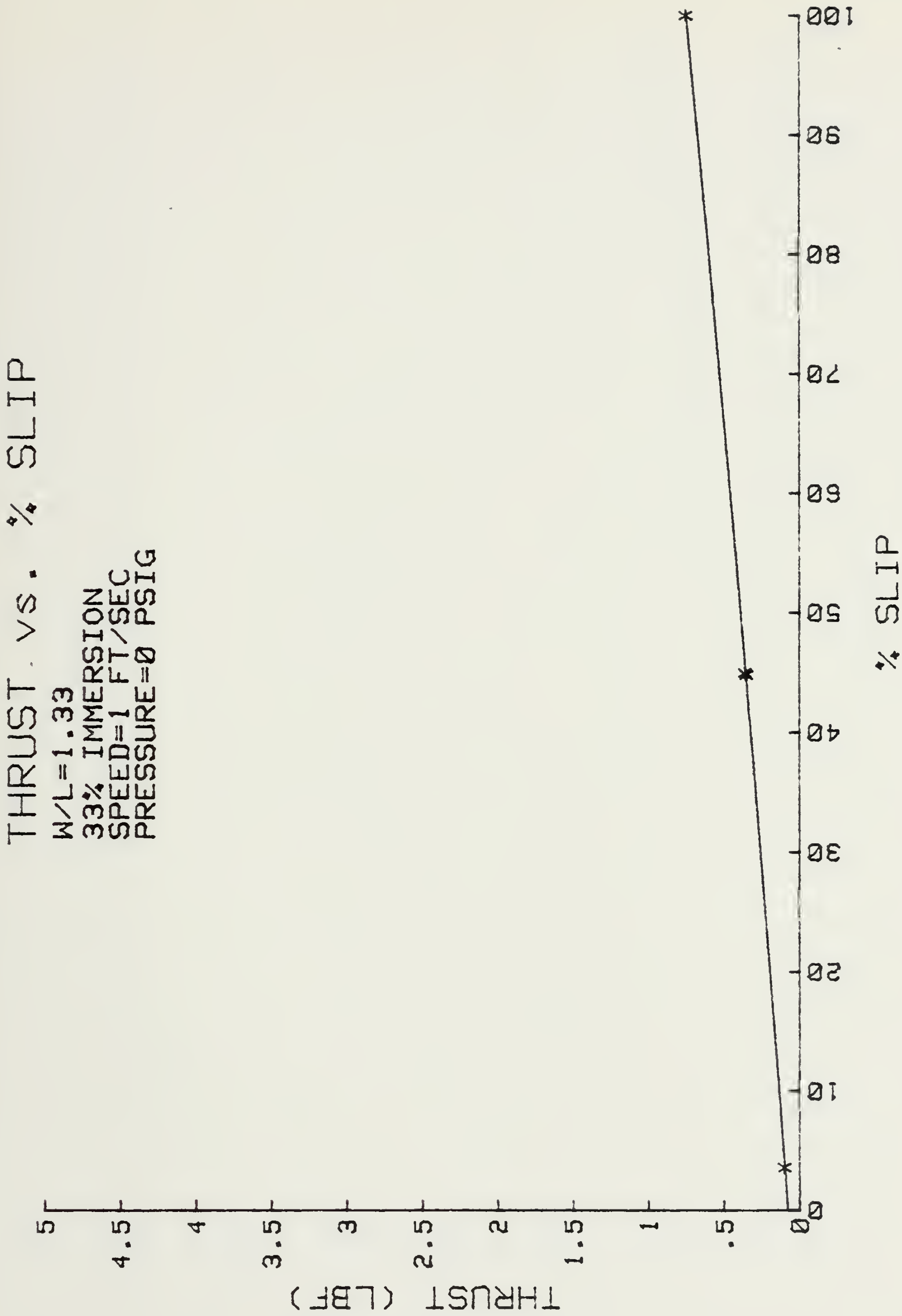

THRUST vs. % SLIP
UNWEBBED
100% IMMERSION
SPEED=1 FT/SEC
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100

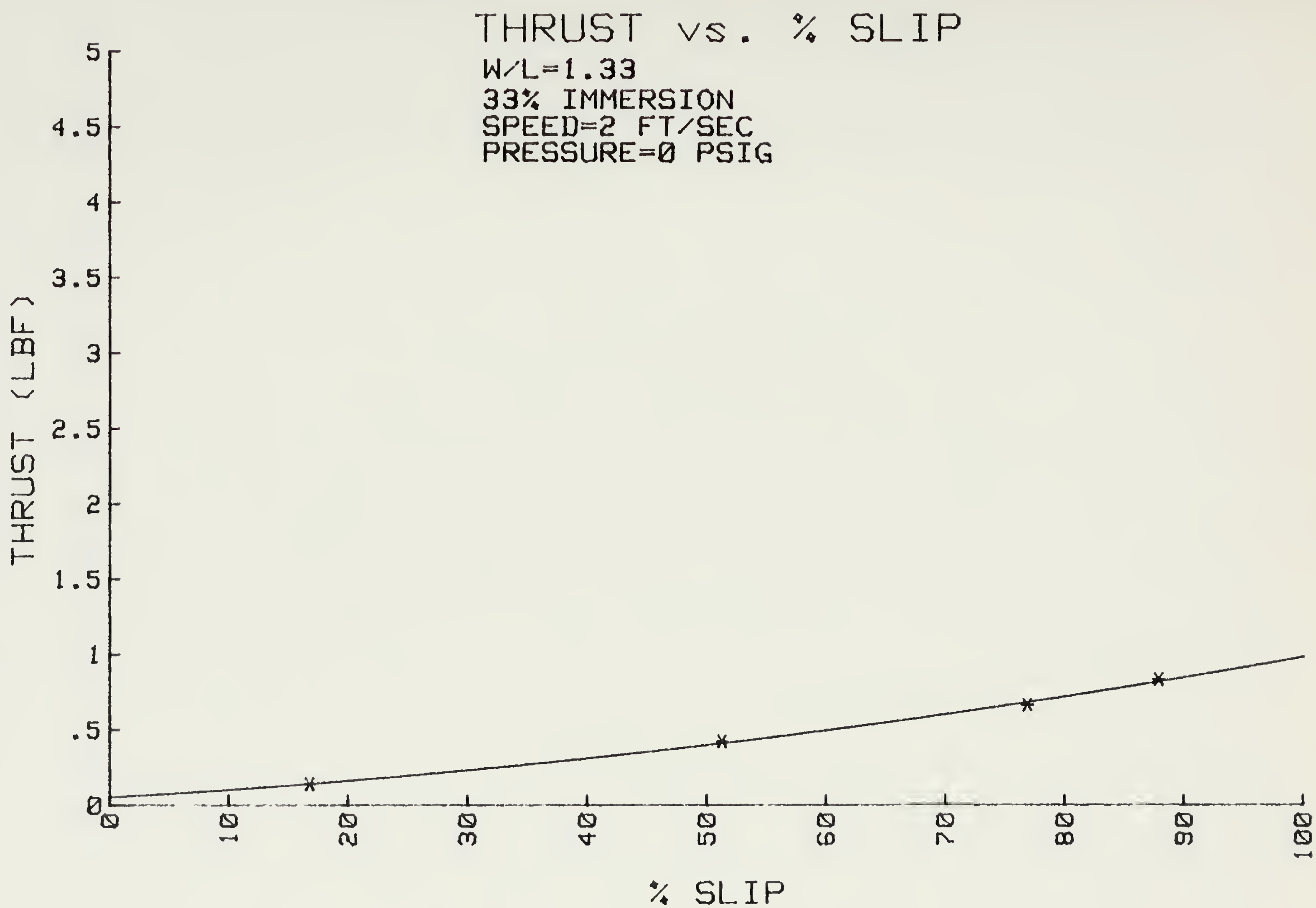

THRUST vs. % SLIP
UNWEBBED
100% IMMERSION
SPEED=2 FT/SEC
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70
80
90
100

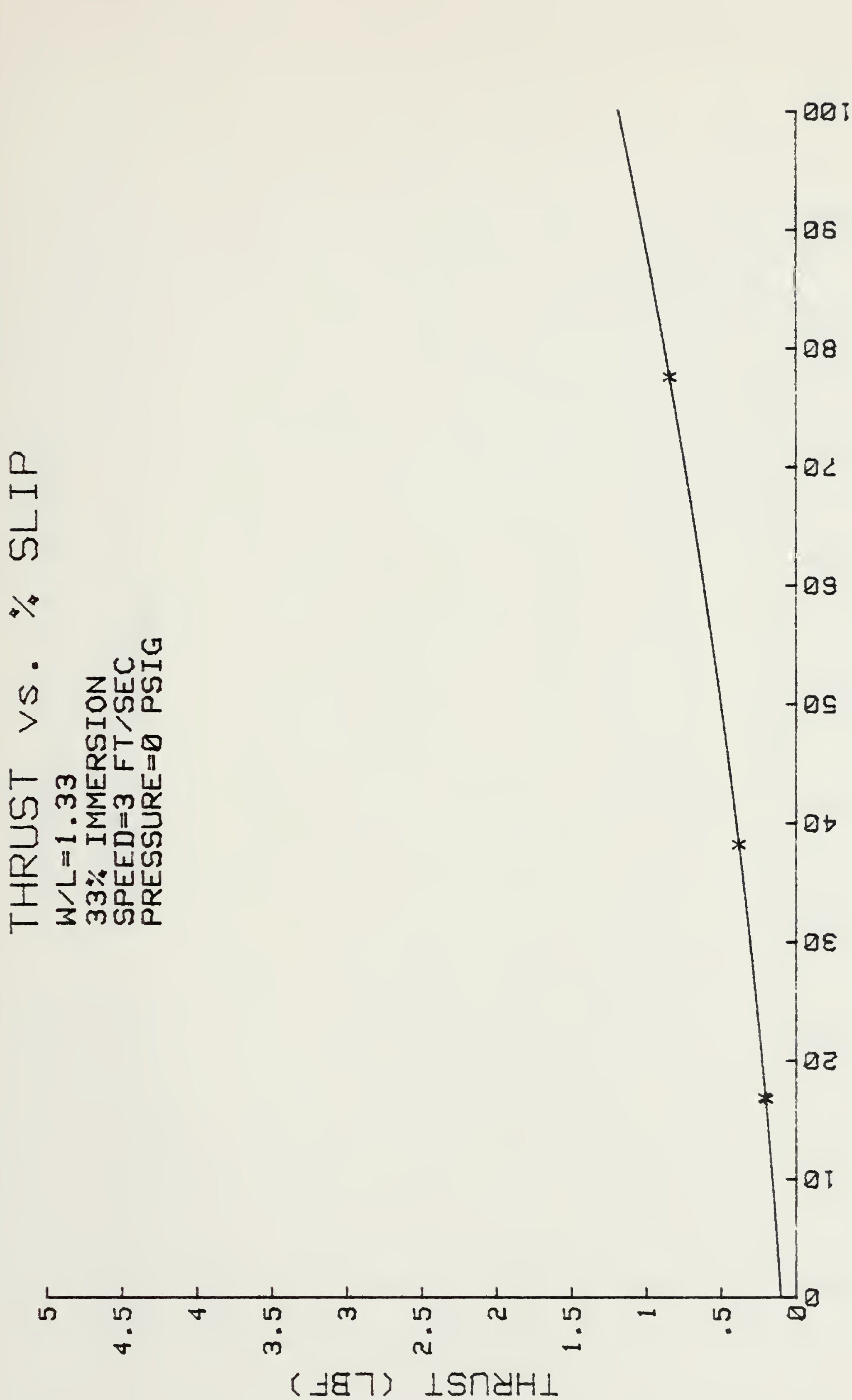


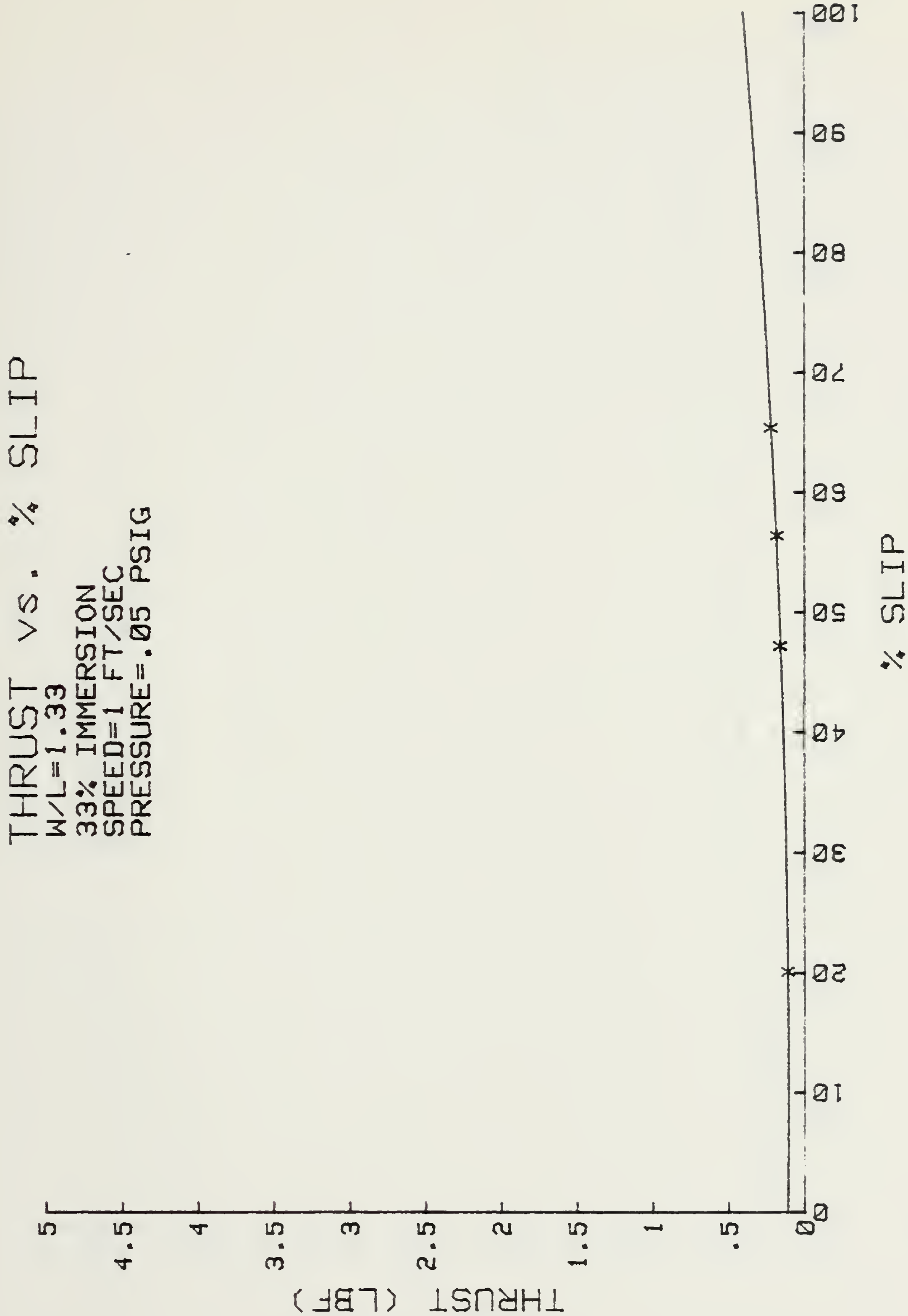
THRUST VS. % SLIP
UNWEBBED
100% IMMERSION
SPEED=3 FT/SEC
THRUST (LBF)
% SLIP

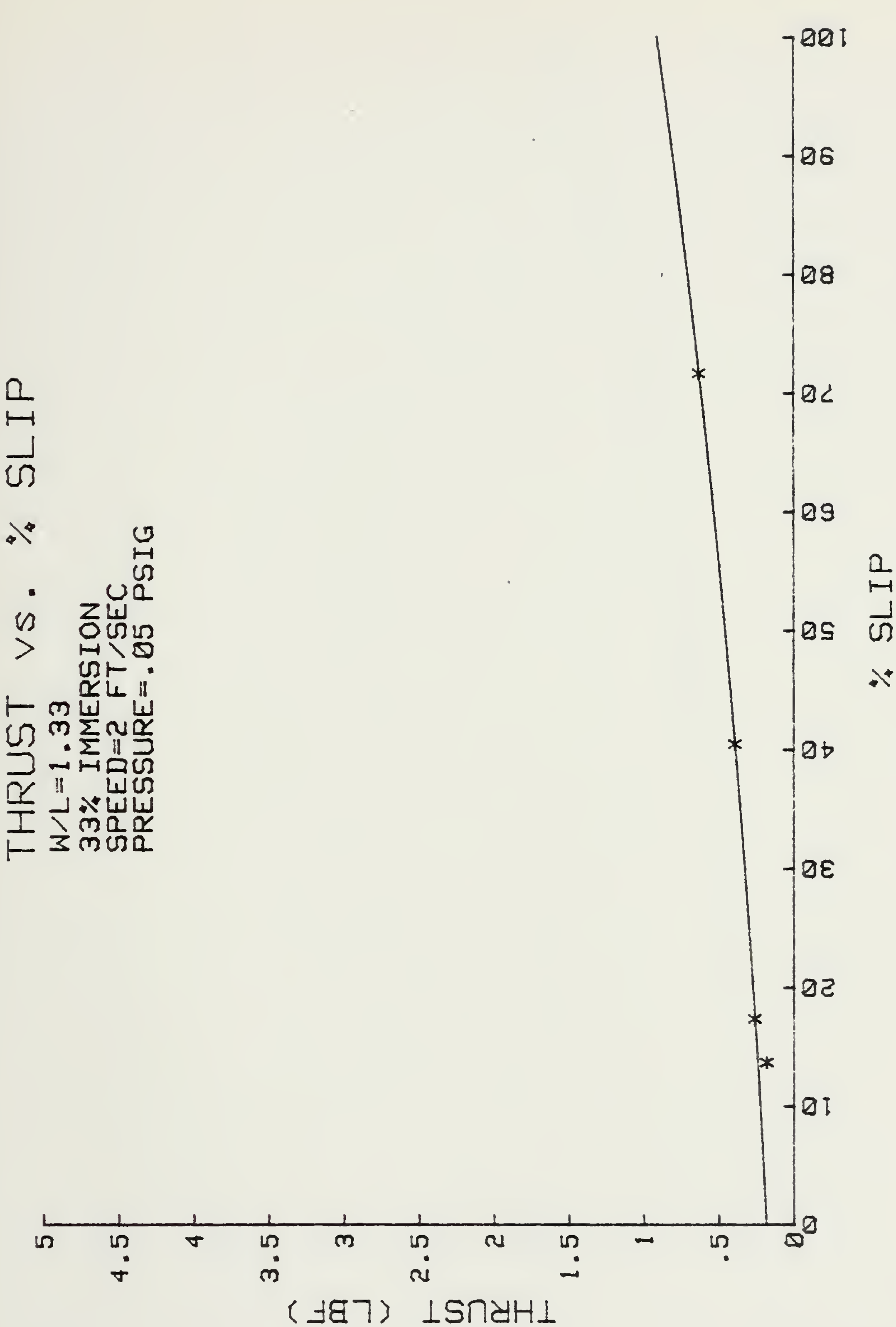

THRUST vs. % SLIP
UNWEBBED
100% IMMERSION
SPEED=4 FT/SEC
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP

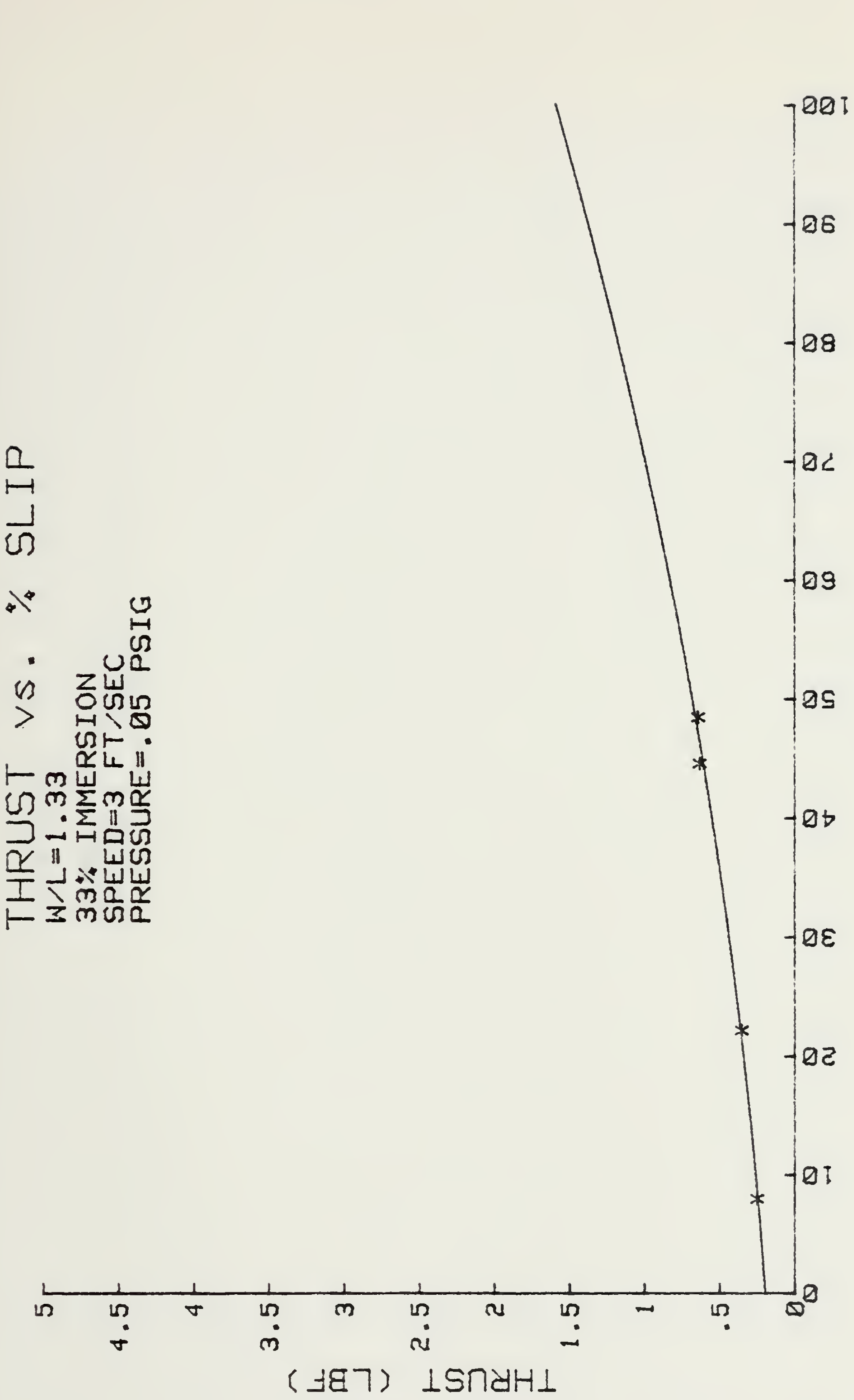

THRUST VS. % SLIP
W/L=1.33
33% IMMERSION
SPEED=1 FT/SEC
PRESSURE=0 PSIG
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70
80
90
100

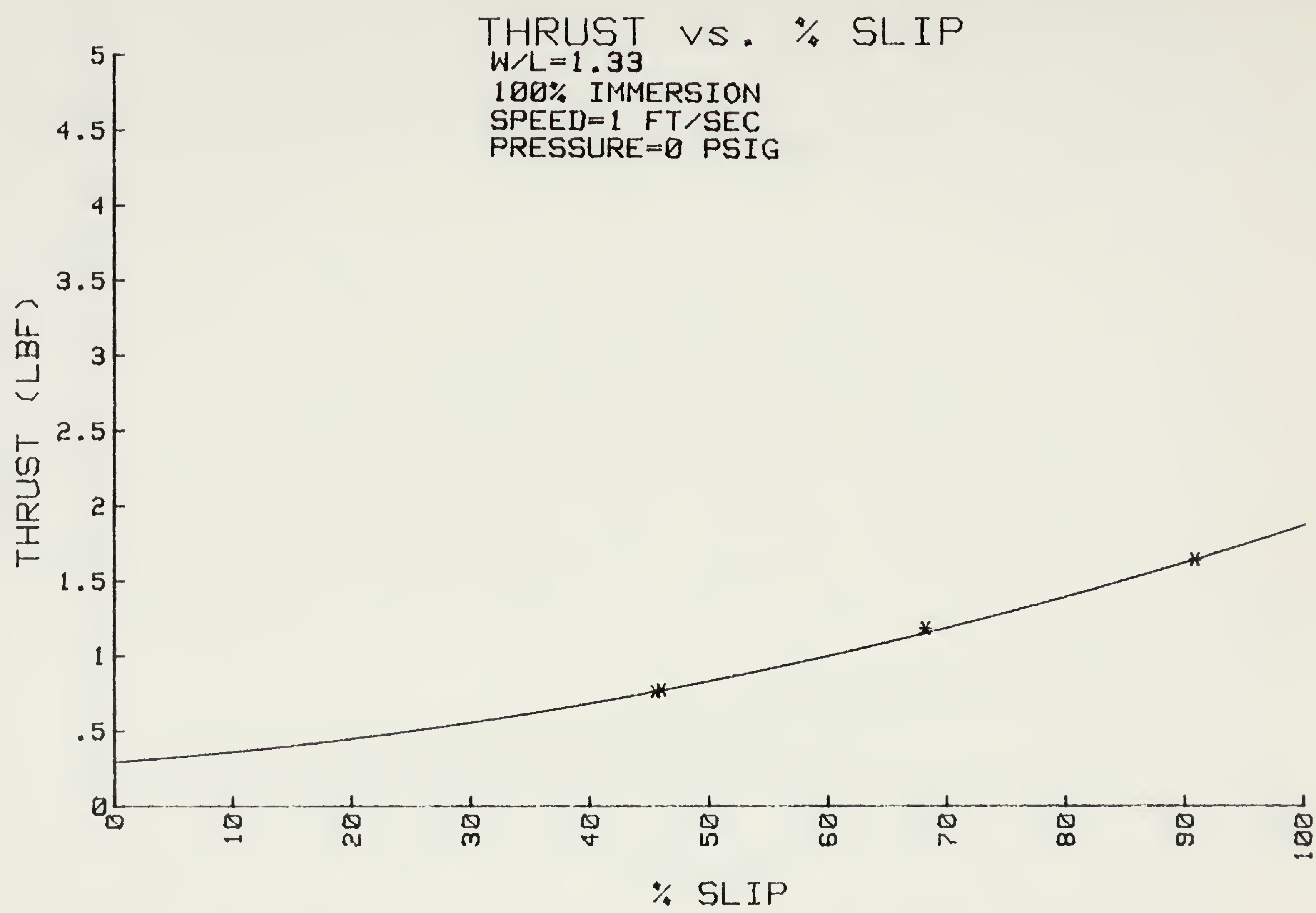

THRUST vs. % SLIP
W/L=1.33
33% IMMERSION
SPEED=2 FT/SEC
PRESSURE=0 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP


THRUST VS. % SLIP
W/L=1.33
33% IMMERSION
SPEED=3 FT/SEC
PRESSURE=0 PSIG
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70
80
90
100

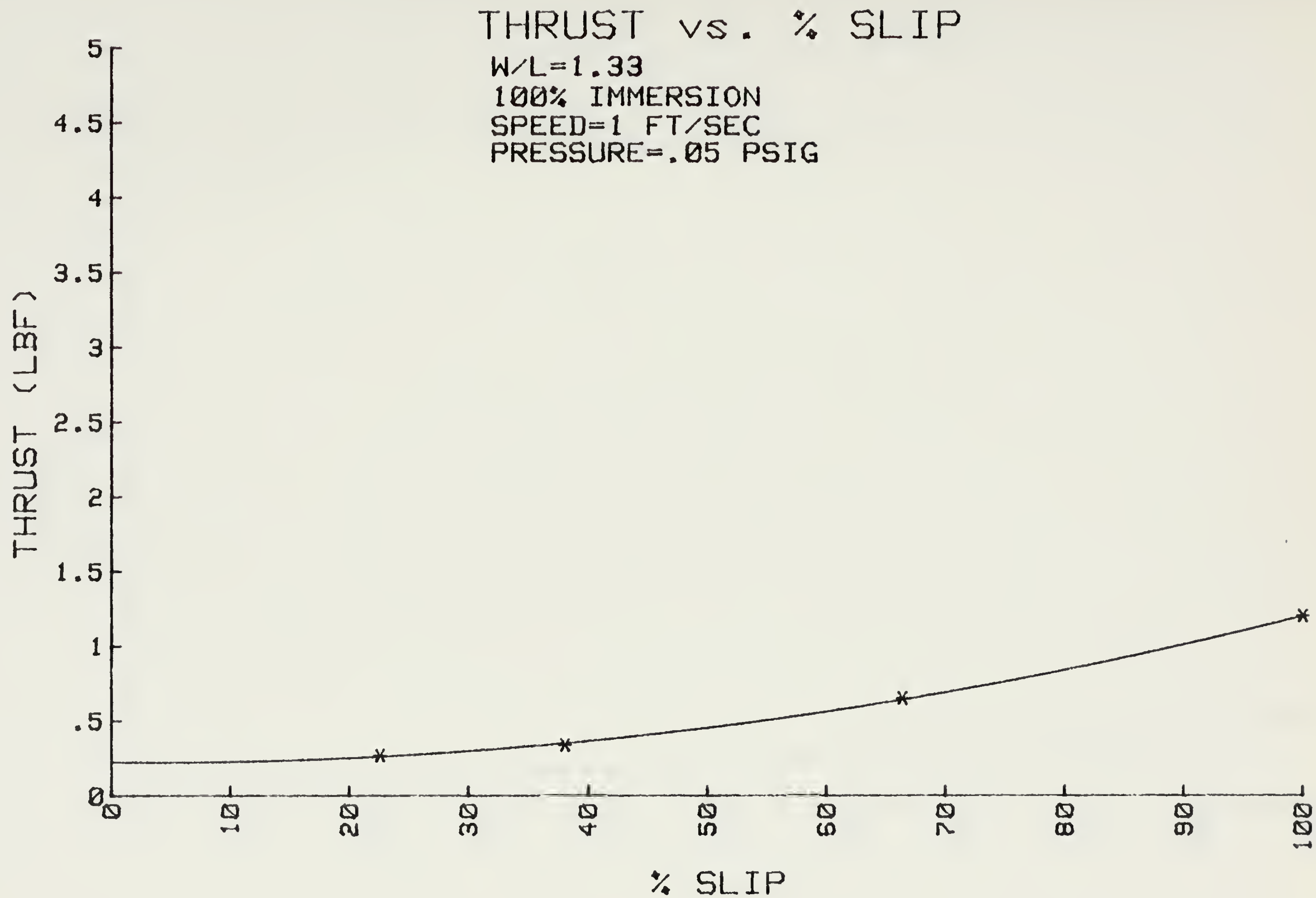

THRUST VS. % SLIP
W/L=1.33
33% IMMERSION
SPEED=1 FT/SEC
PRESSURE=.05 PSIG
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70
80
90
100

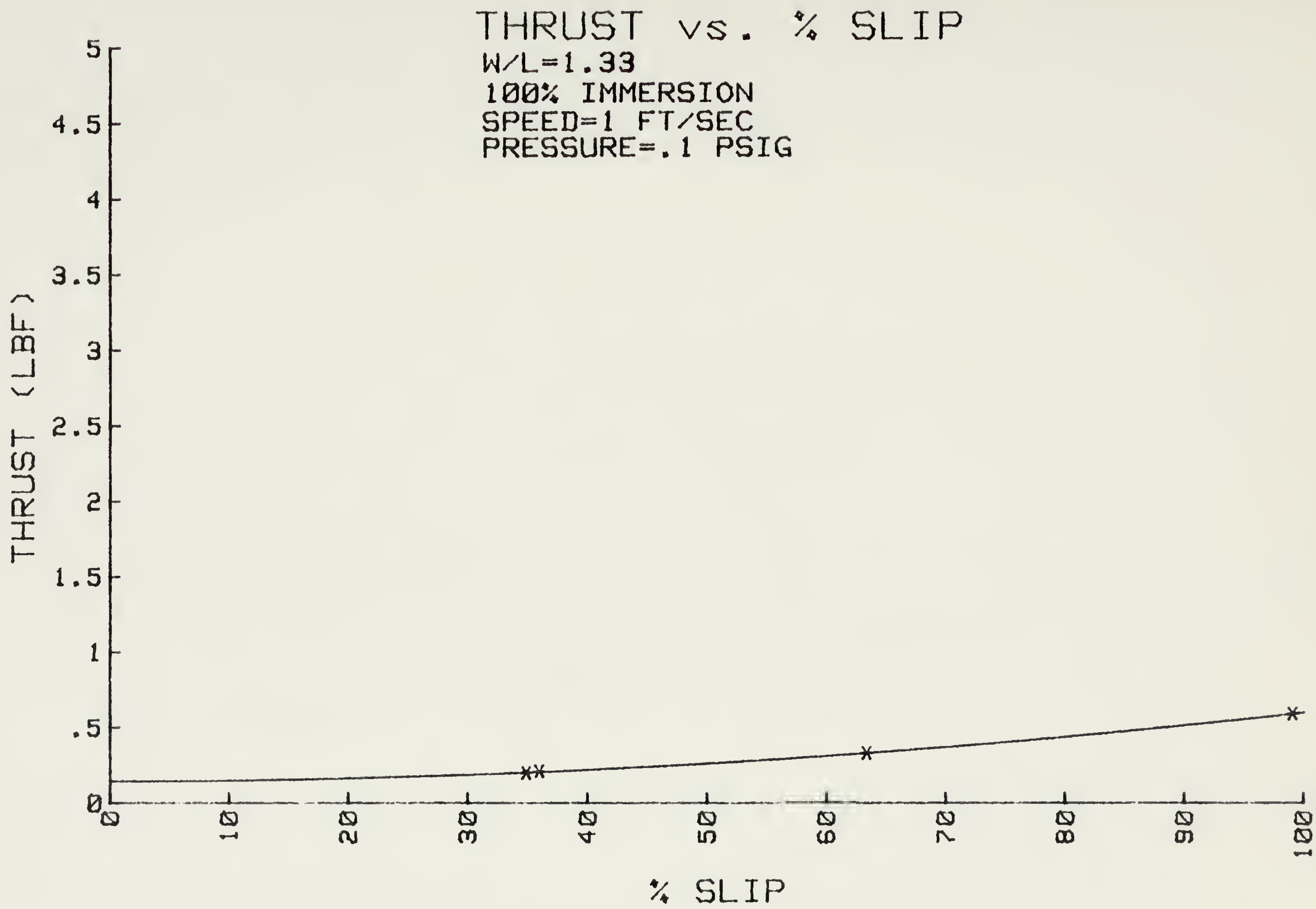

THRUST VS. % SLIP
W/L=1.33
33% IMMERSION
SPEED=2 FT/SEC
PRESSURE=.05 PSIG
THRUST (LBF)
% SLIP
0
10
20
30
40
50
60
70
80
90
100
.5
1
1.5
2
2.5
3
3.5
4
4.5
5

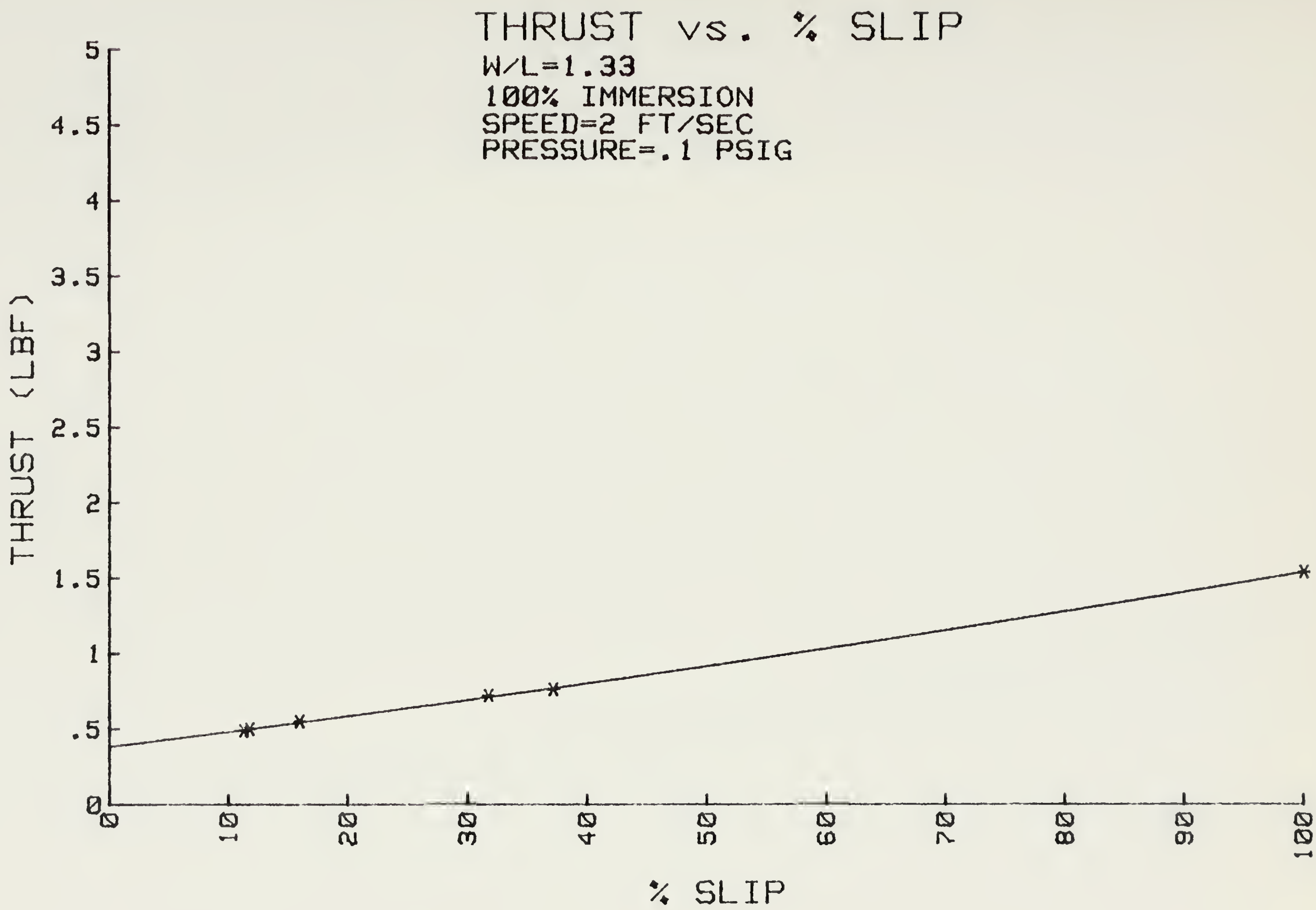

THRUST VS. % SLIP
W/L=1.33
33% IMMERSION
SPEED=3 FT/SEC
PRESSURE=.05 PSIG
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70
80
90
100



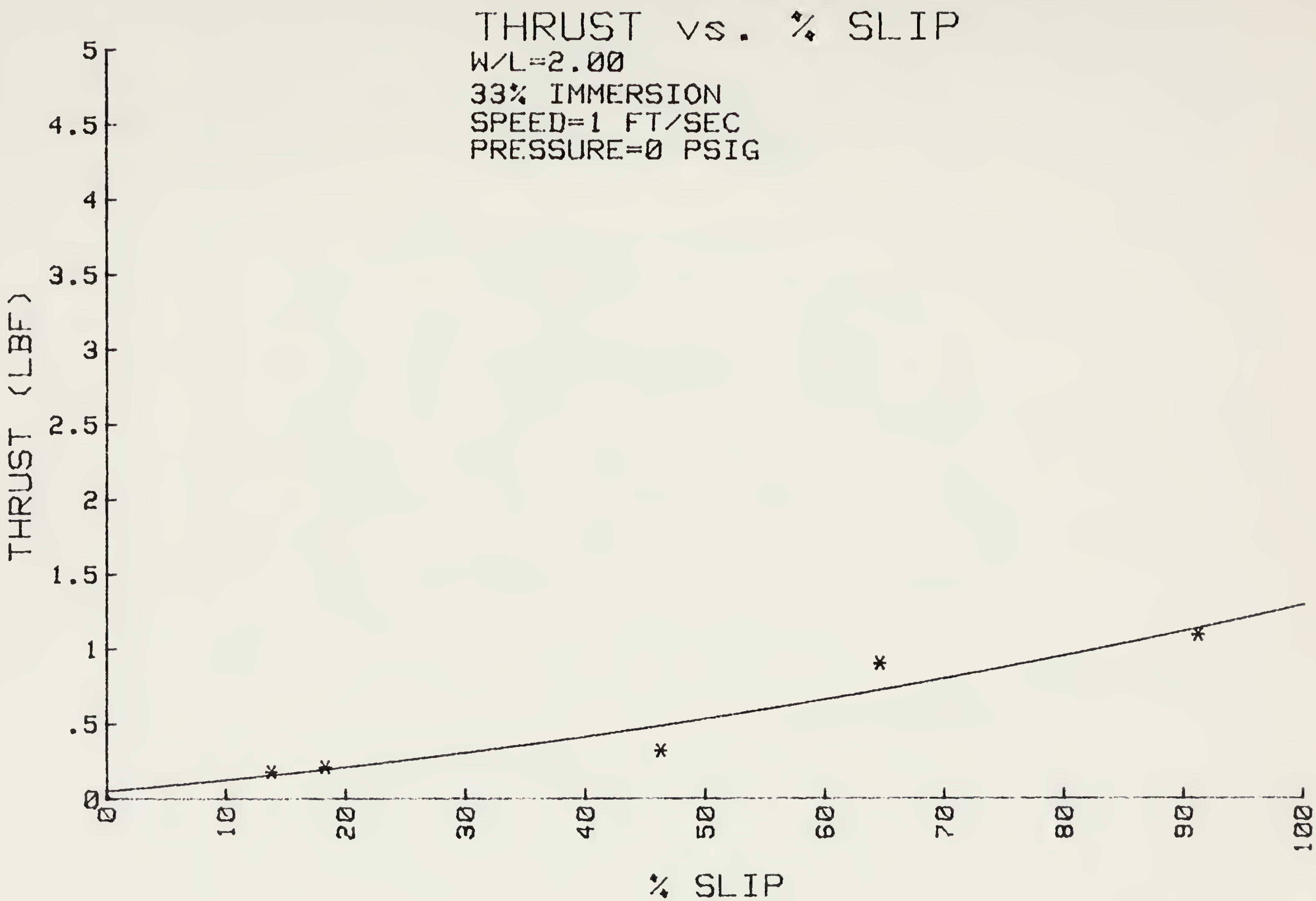
THRUST vs. % SLIP
W/L=1.33
100% IMMERSION
SPEED=1 FT/SEC
PRESSURE=0 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP

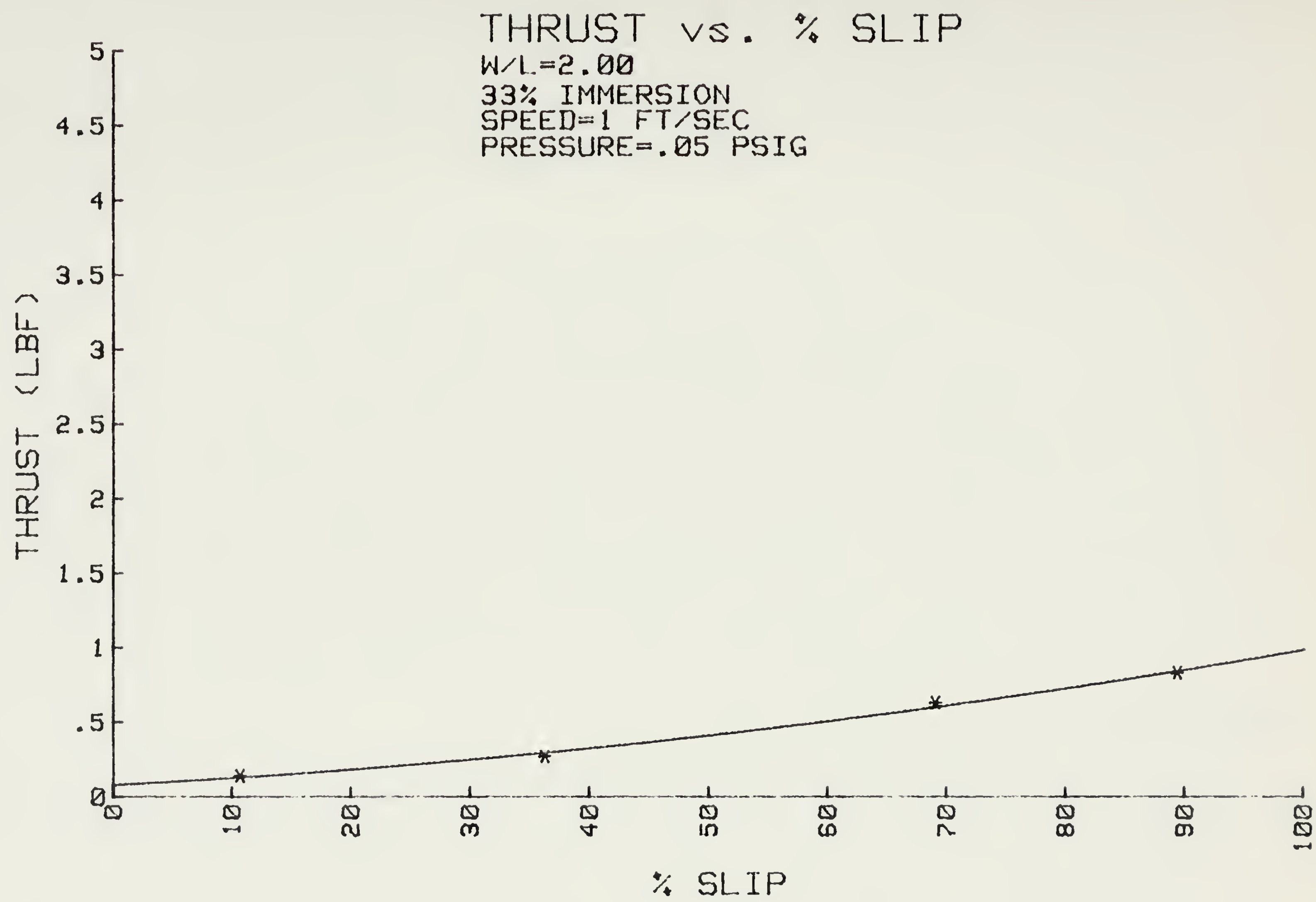

THRUST vs. % SLIP
W/L=1.33
100% IMMERSION
SPEED=1 FT/SEC
PRESSURE=.05 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP

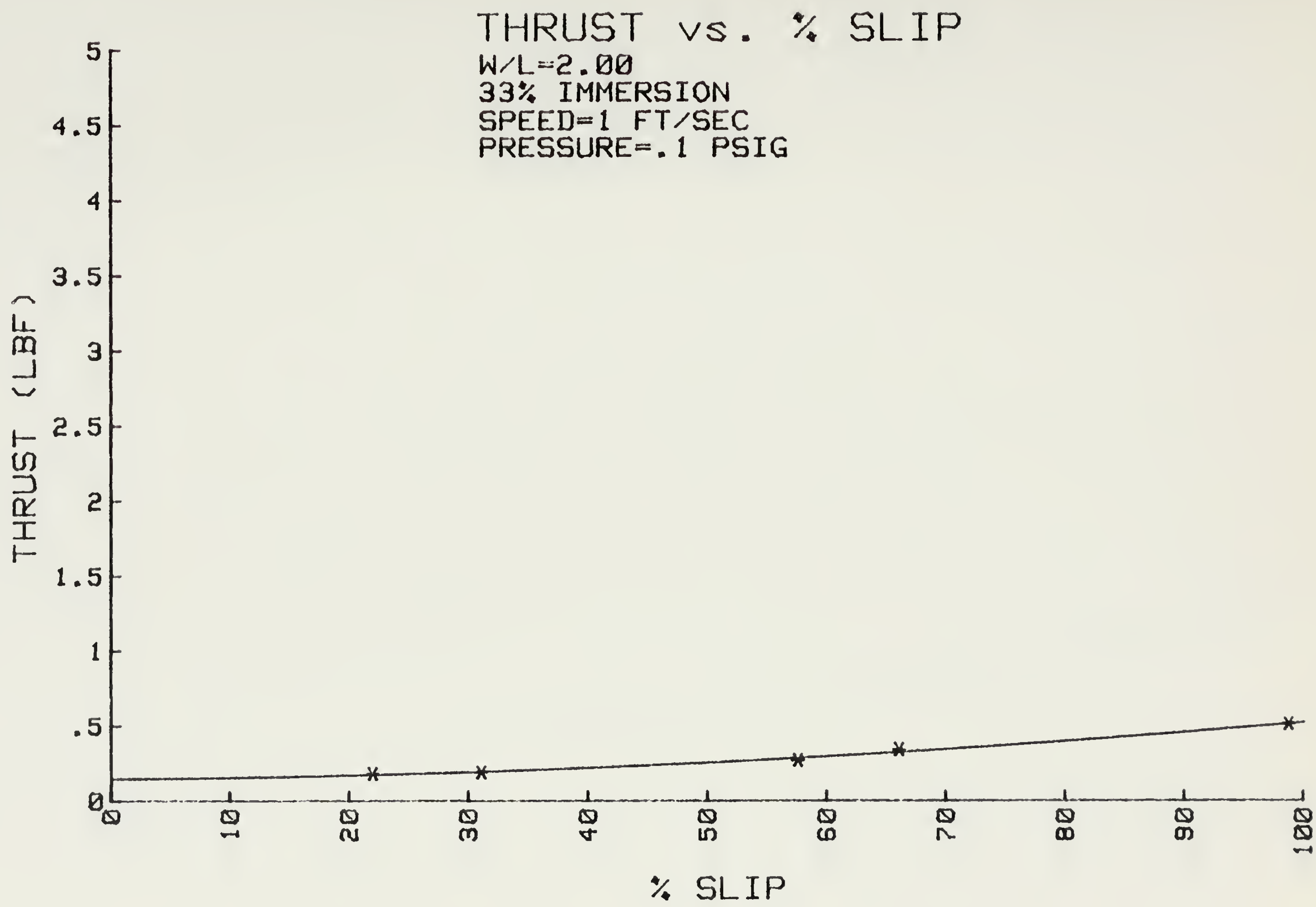

THRUST vs. % SLIP
W/L=1.33
100% IMMERSION
SPEED=1 FT/SEC
PRESSURE=.1 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP

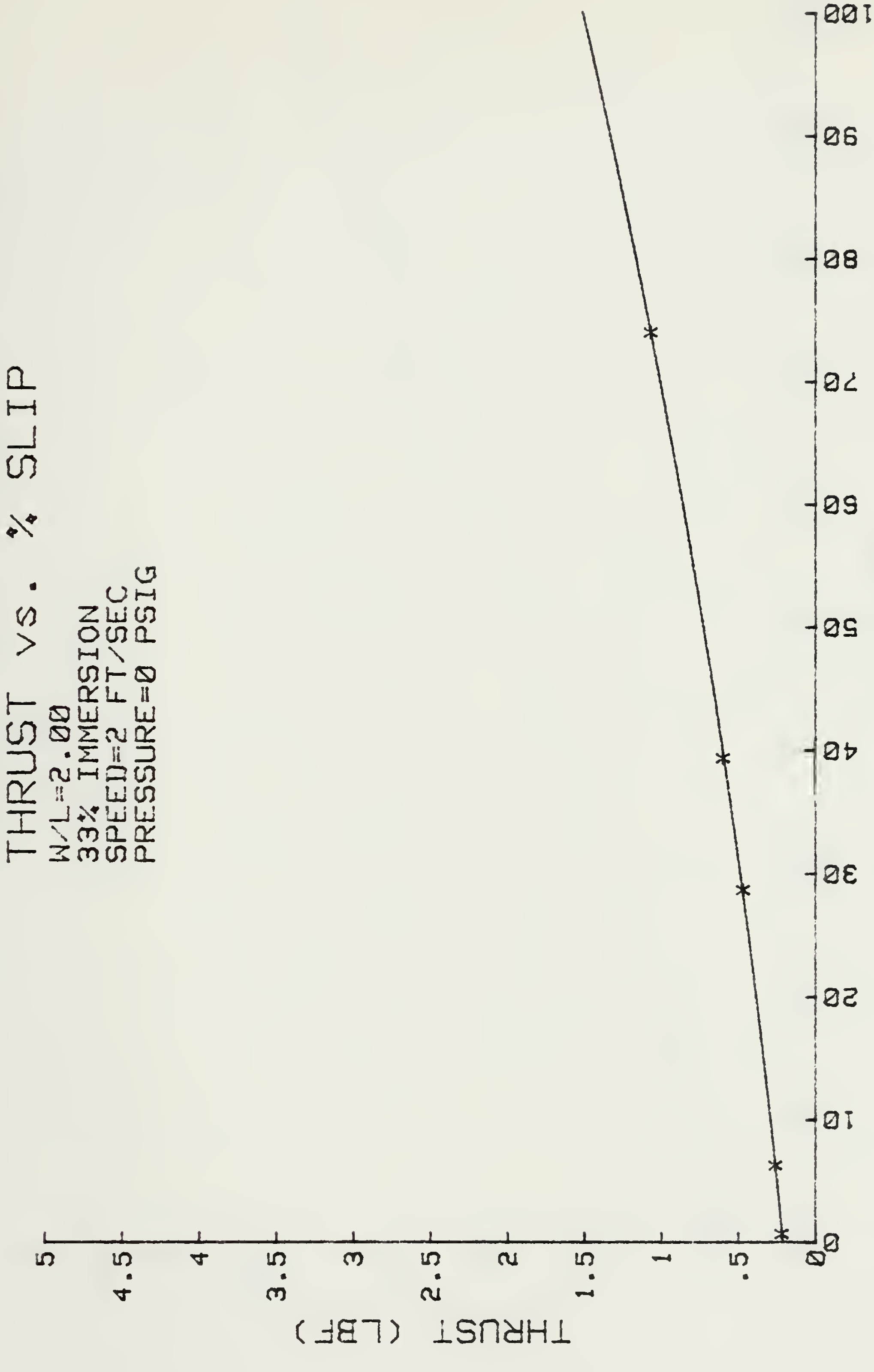


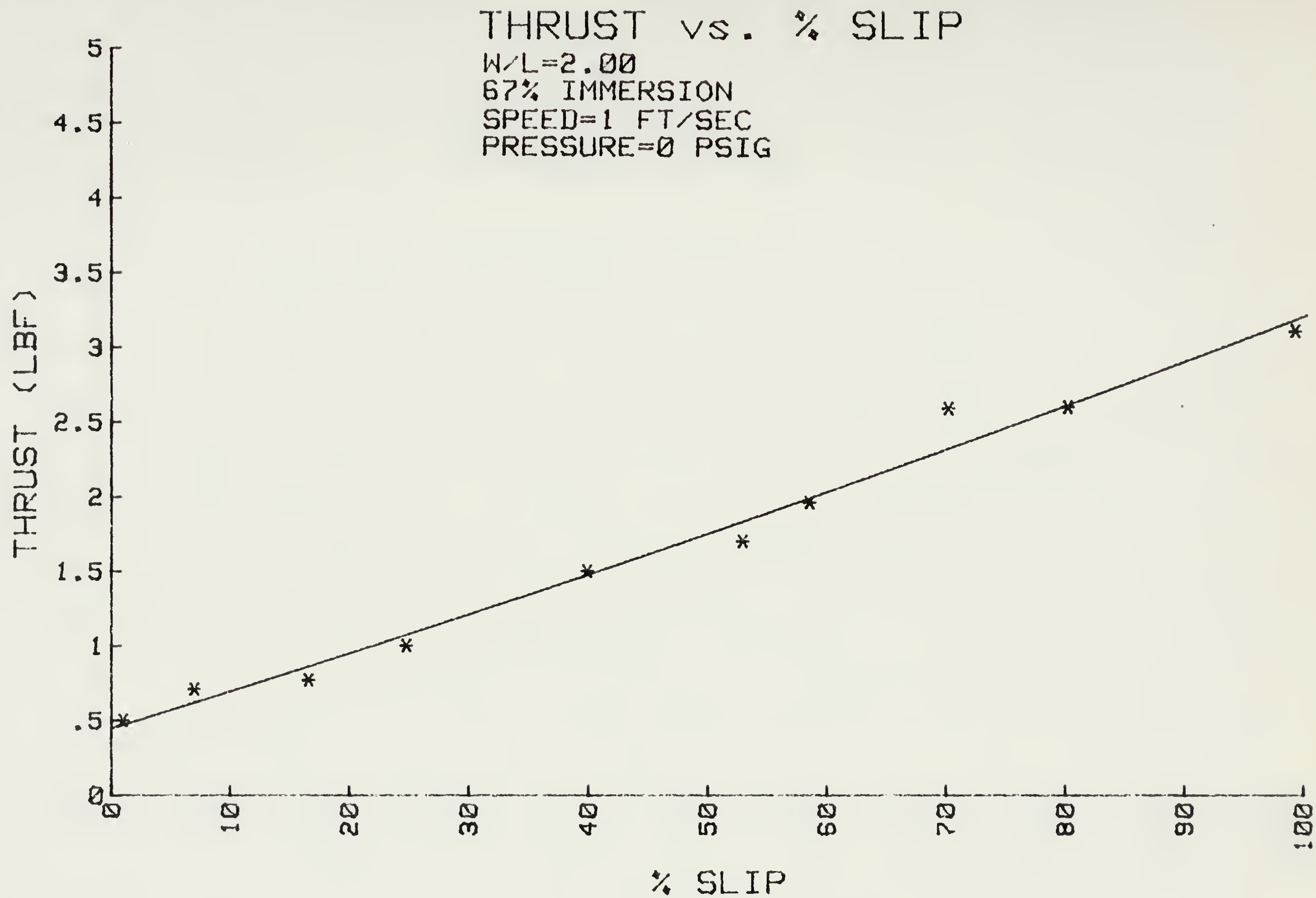
THRUST vs. % SLIP
W/L=1.33
100% IMMERSION
SPEED=2 FT/SEC
PRESSURE=.1 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP

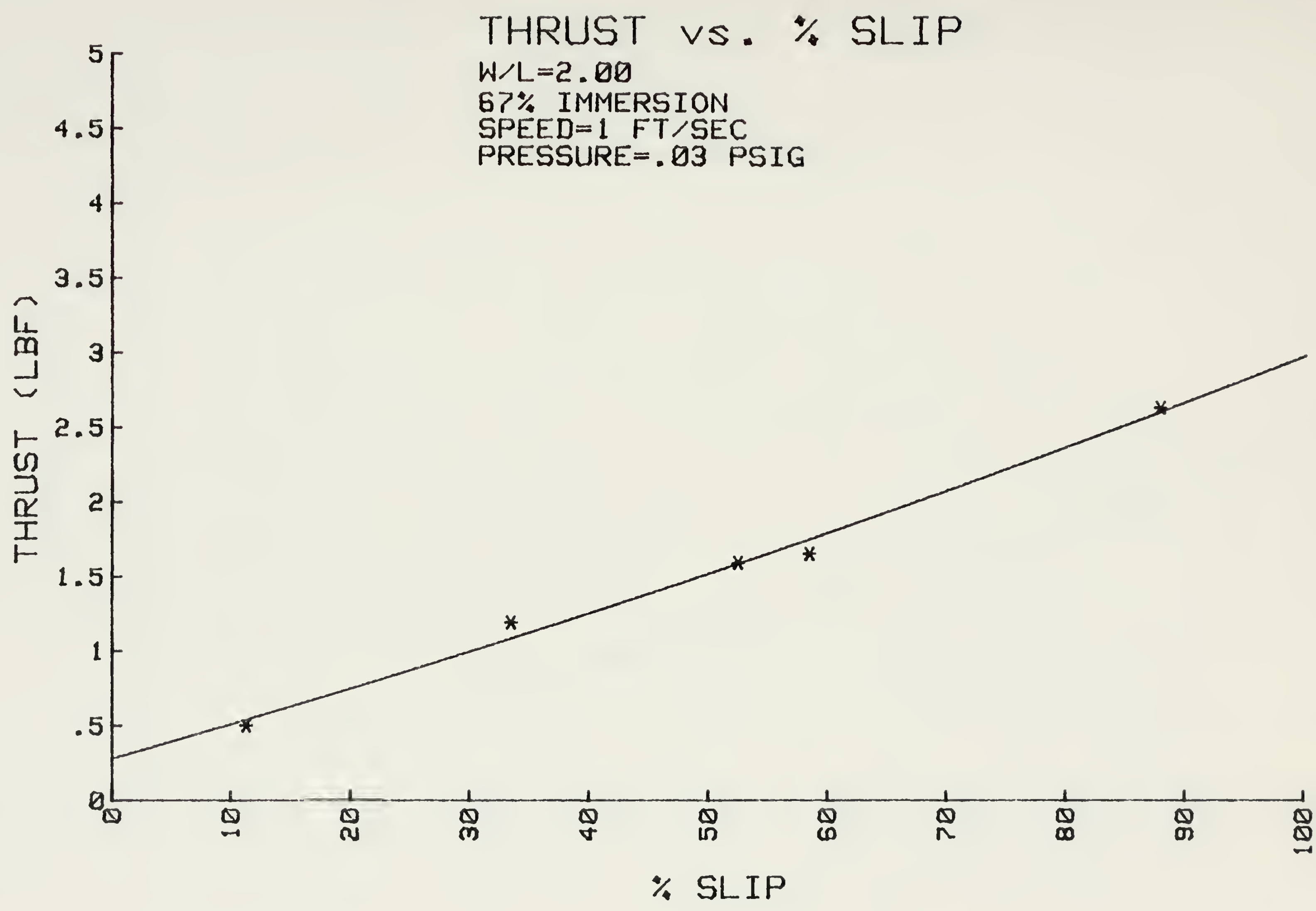

THRUST vs. % SLIP
W/L=2.00
33% IMMERSION
SPEED=1 FT/SEC
PRESSURE=0 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP

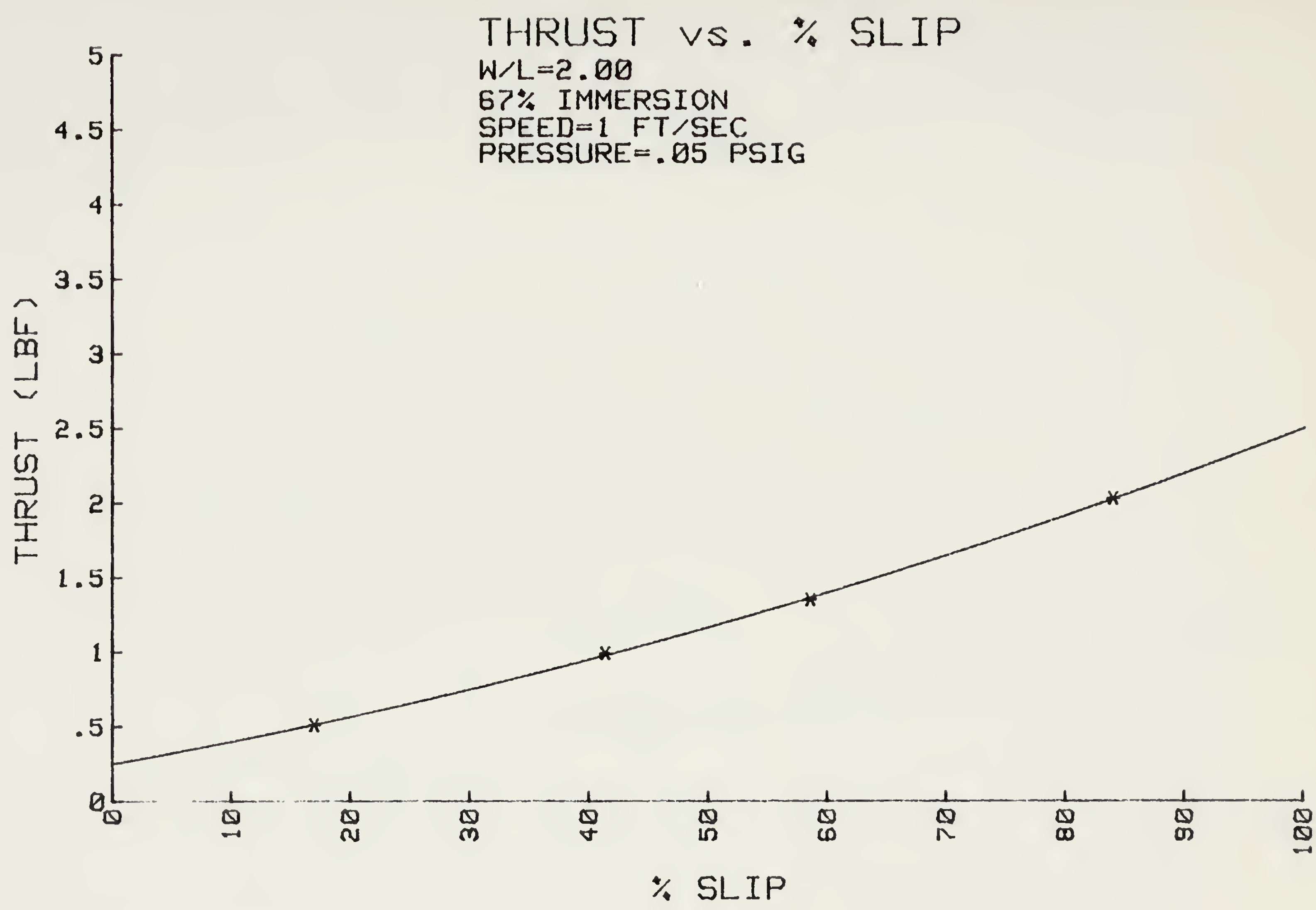

THRUST vs. % SLIP
W/L=2.00
33% IMMERSION
SPEED=1 FT/SEC
PRESSURE=.05 PSIG
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100


THRUST vs. % SLIP
W/L=2.00
33% IMMERSION
SPEED=1 FT/SEC
PRESSURE=.1 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP

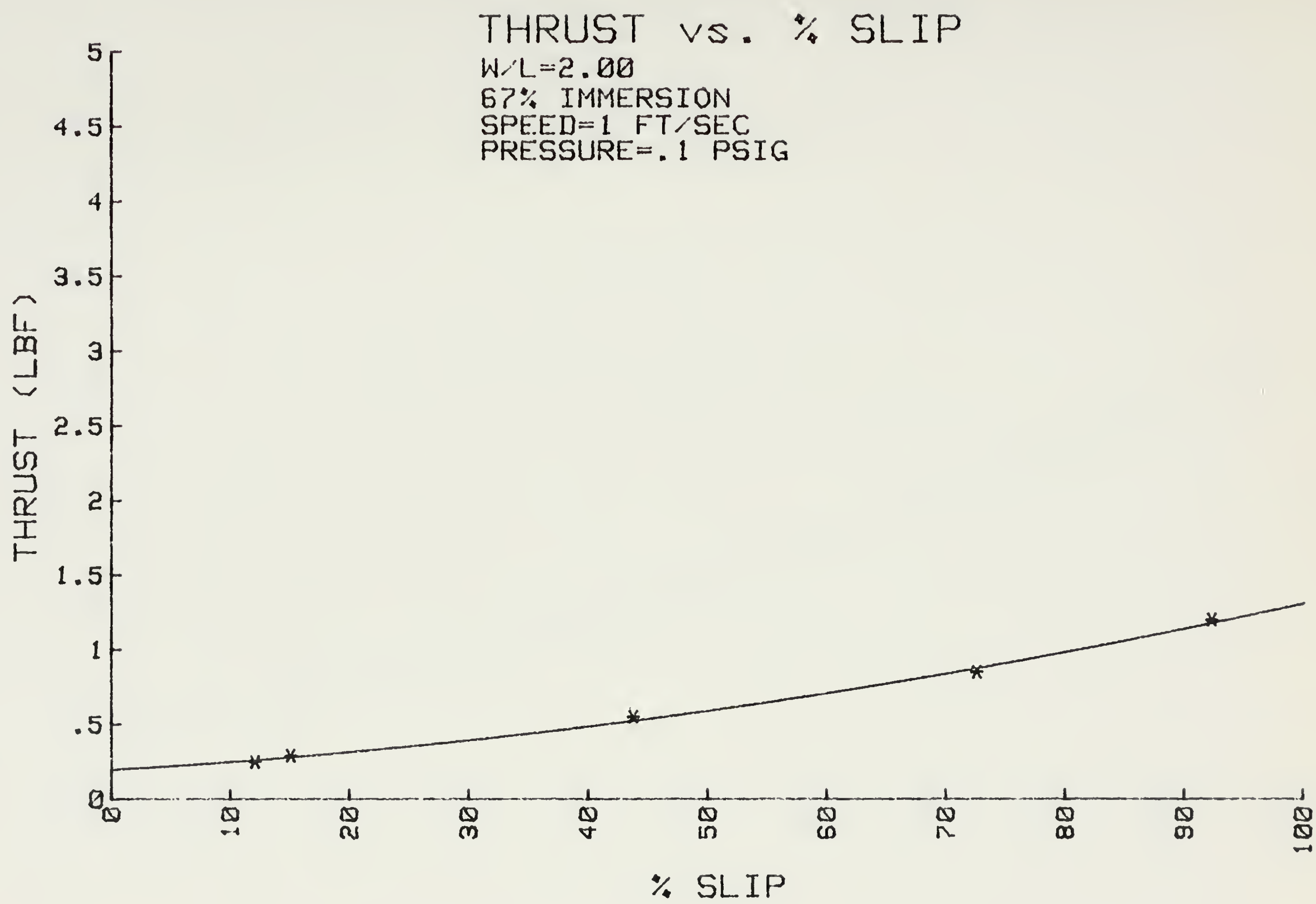

THRUST VS. % SLIP
W/L=2.00
33% IMMERSION
SPEED=2 FT/SEC
PRESSURE=0 PSIG
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70
80
90
100


THRUST vs. % SLIP
W/L=2.00
67% IMMERSION
SPEED=1 FT/SEC
PRESSURE=0 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP

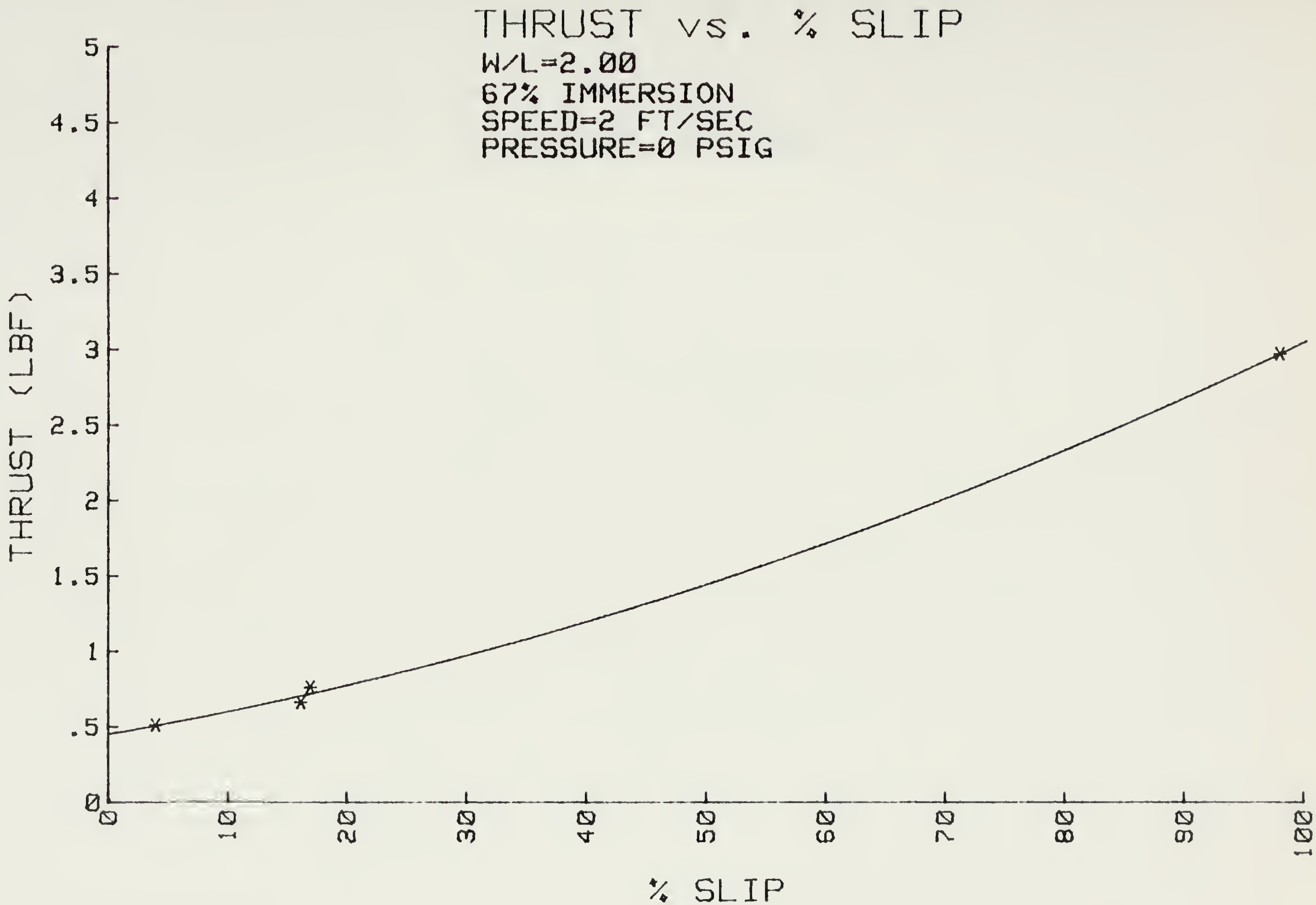

THRUST vs. % SLIP
W/L=2.00
67% IMMERSION
SPEED=1 FT/SEC
PRESSURE=.03 PSIG
THRUST (LBF)
5
4.5
4
3.5
3
2.5
2
1.5
1
.5
0
0
10
20
30
40
50
60
70
80
90
100
% SLIP

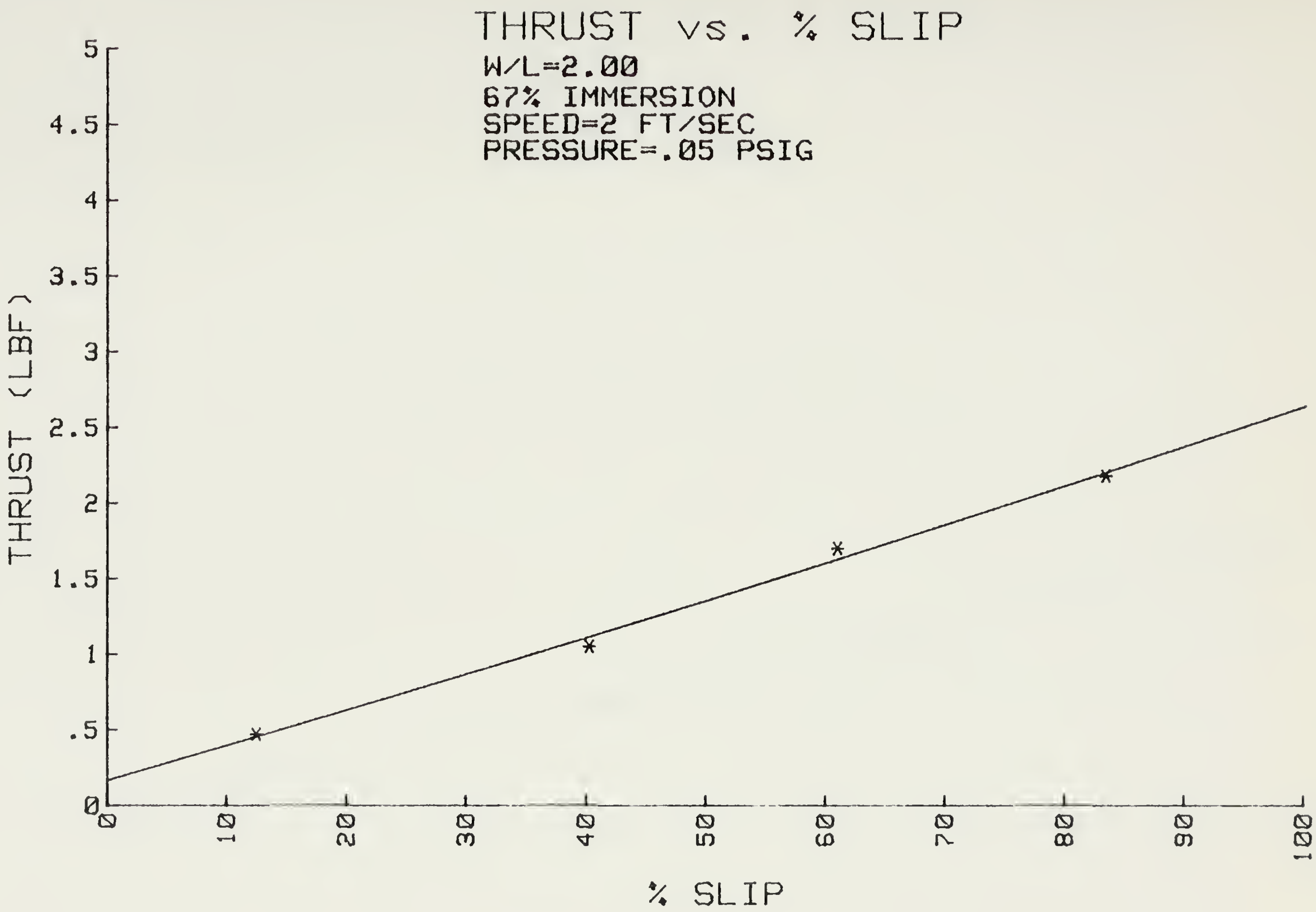


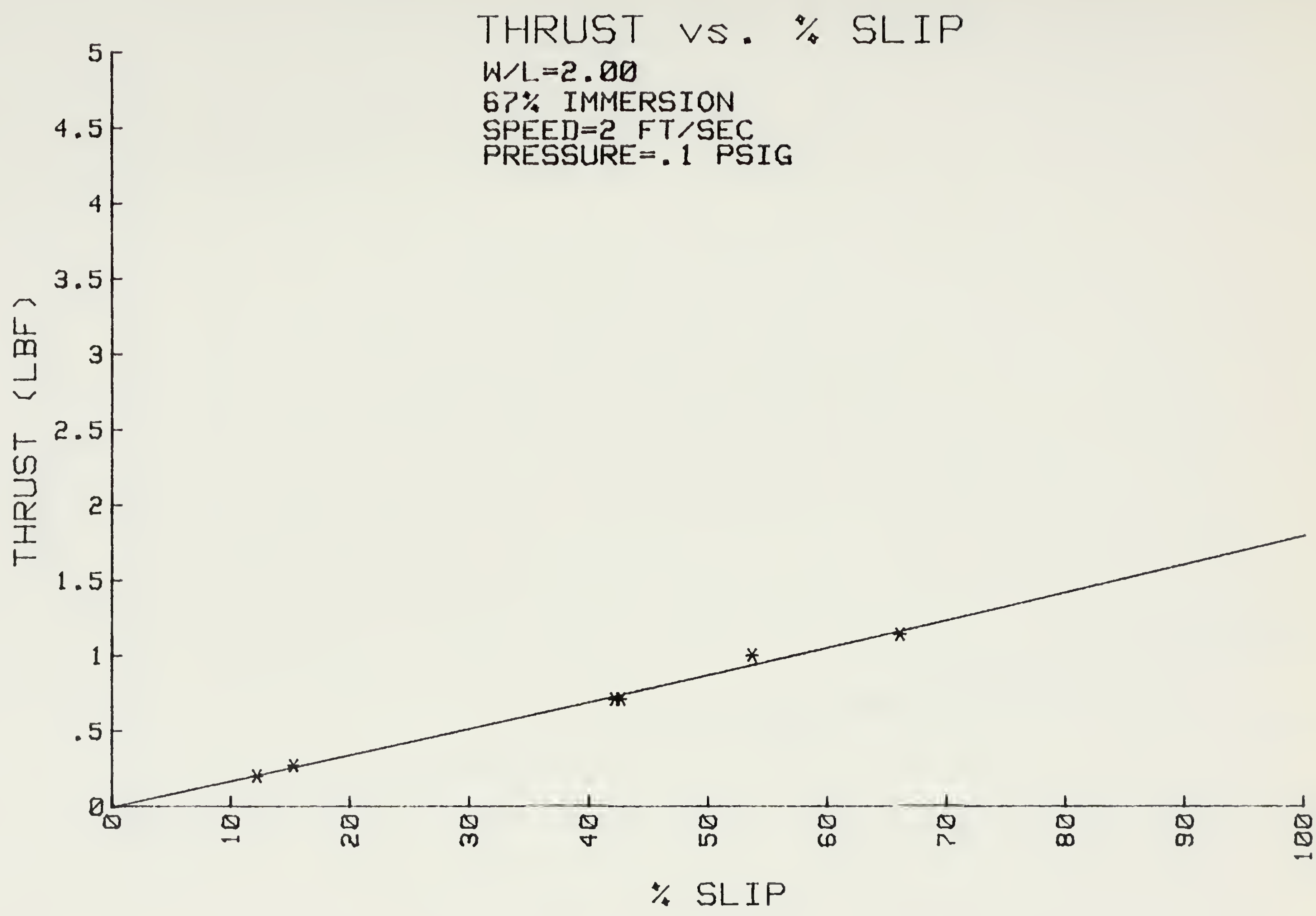
THRUST vs. % SLIP
W/L=2.00
67% IMMERSION
SPEED=1 FT/SEC
PRESSURE=.05 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP



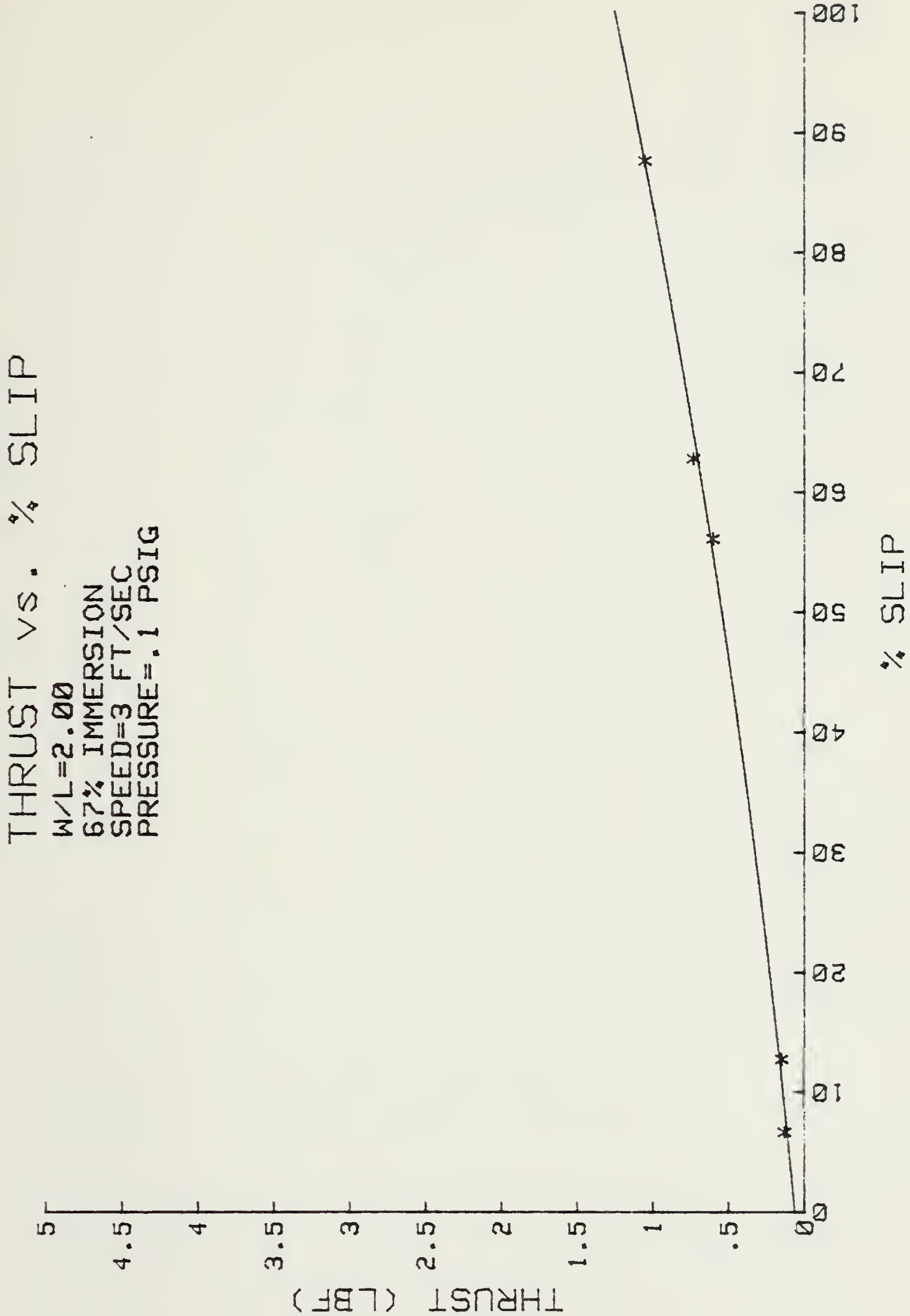
THRUST vs. % SLIP
W/L=2.00
67% IMMERSION
SPEED=1 FT/SEC
PRESSURE=.1 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP


THRUST vs. % SLIP
W/L=2.00
67% IMMERSION
SPEED=2 FT/SEC
PRESSURE=0 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
% SLIP
0
10
20
30
40
50
60
70
80
90
100

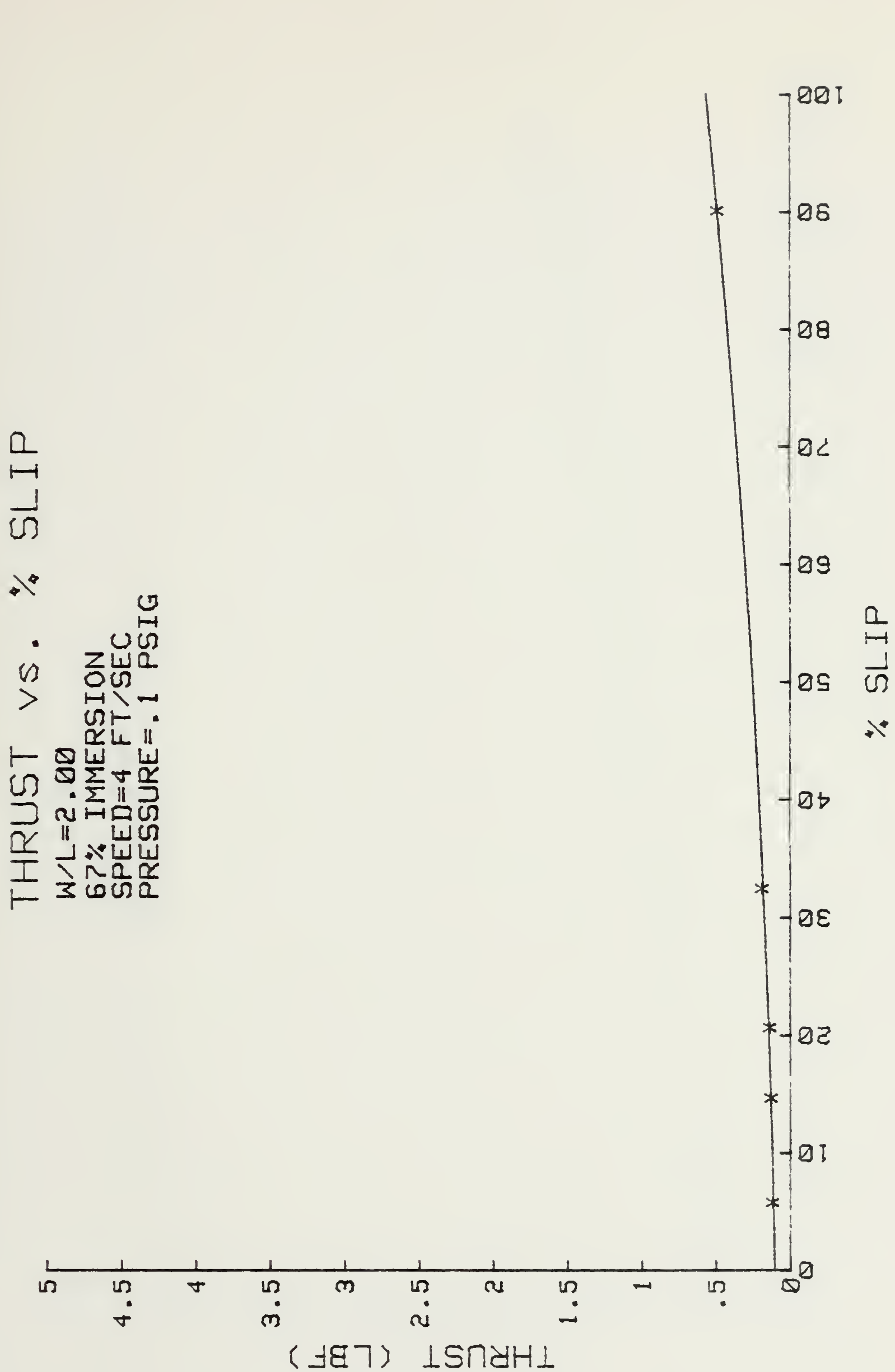

THRUST vs. % SLIP
W/L=2.00
67% IMMERSION
SPEED=2 FT/SEC
PRESSURE=.05 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
% SLIP
0
10
20
30
40
50
60
70
80
90
100

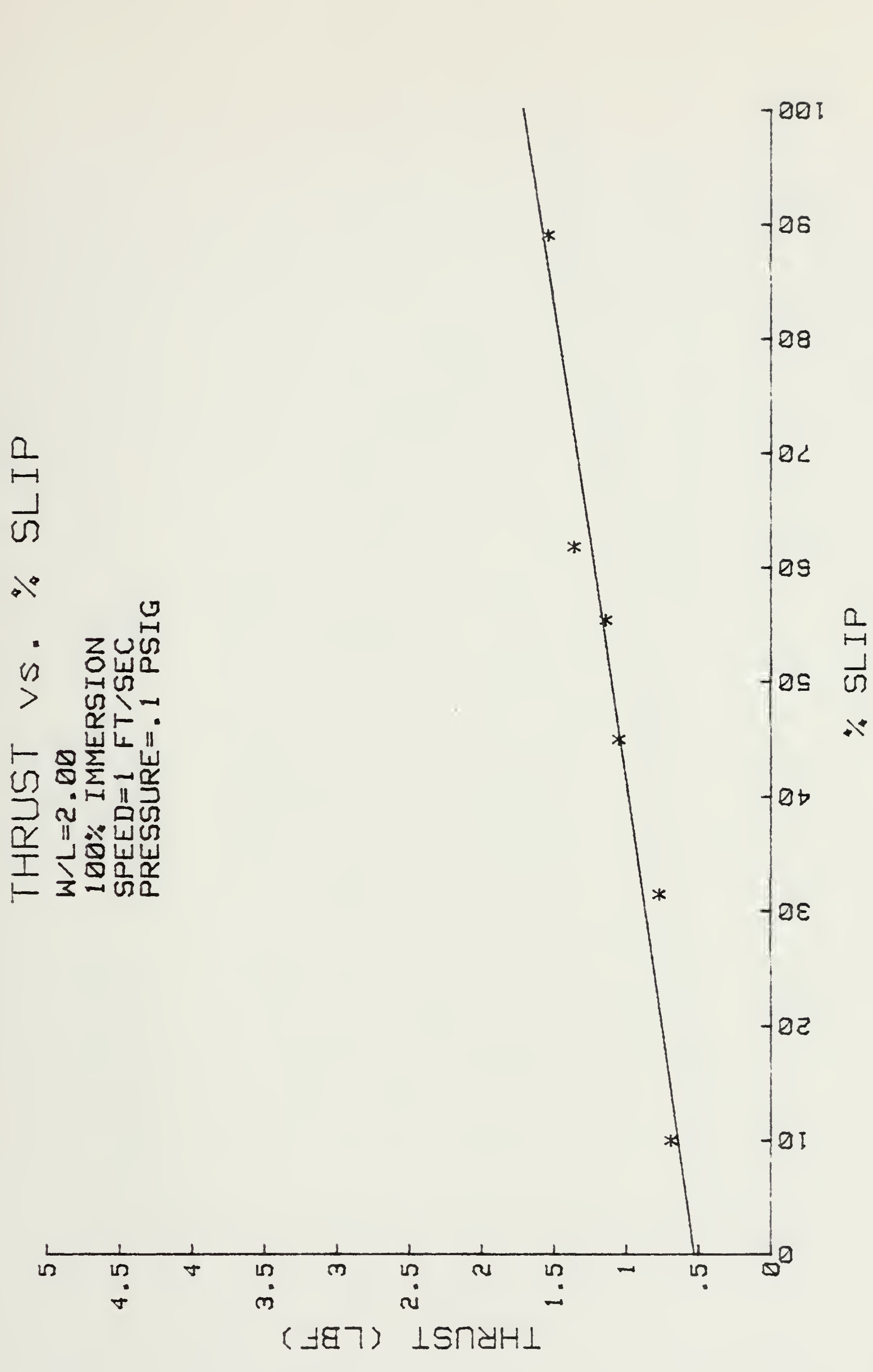


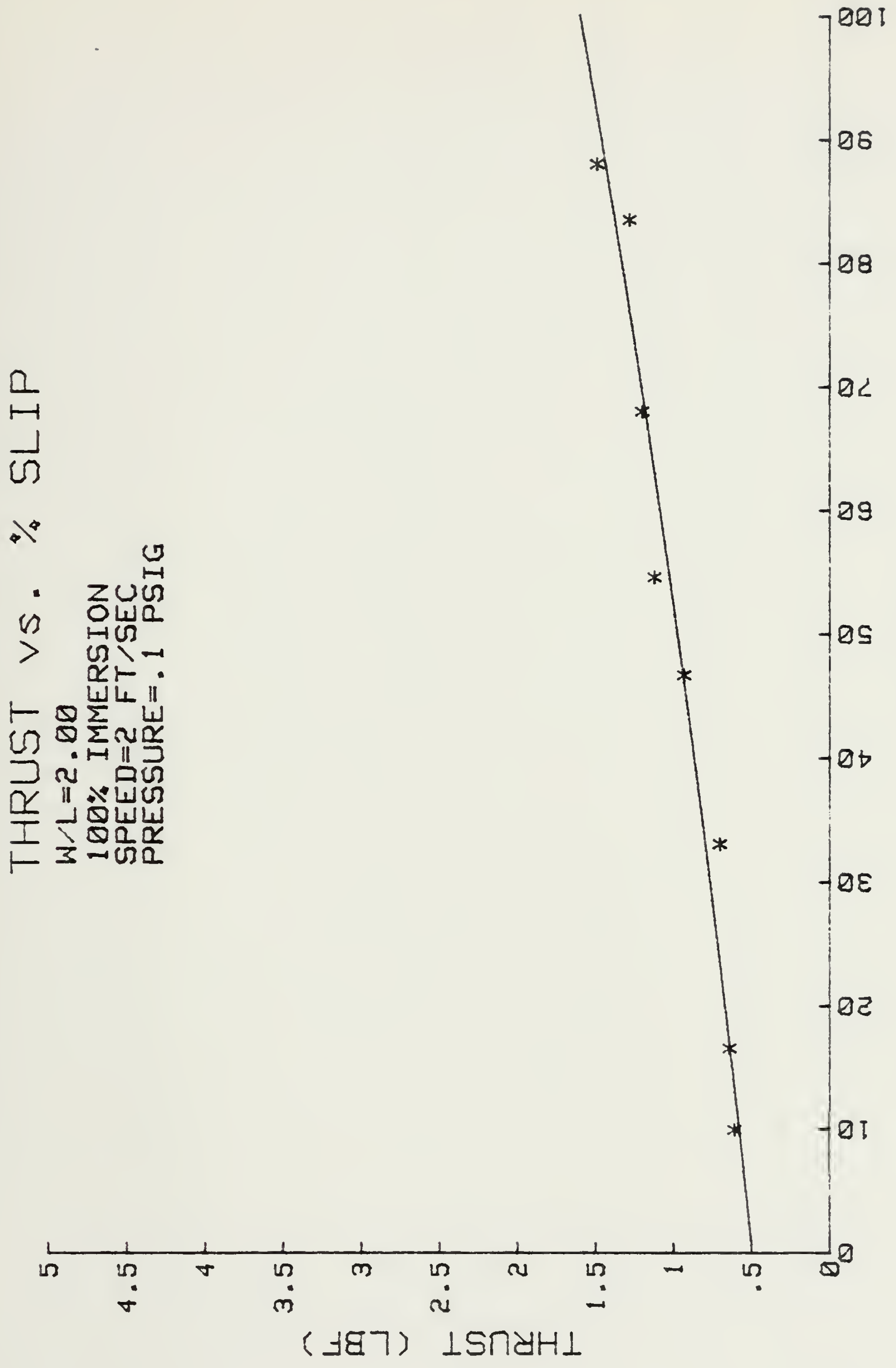
THRUST vs. % SLIP
W/L=2.00
67% IMMERSION
SPEED=2 FT/SEC
PRESSURE=.1 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
% SLIP

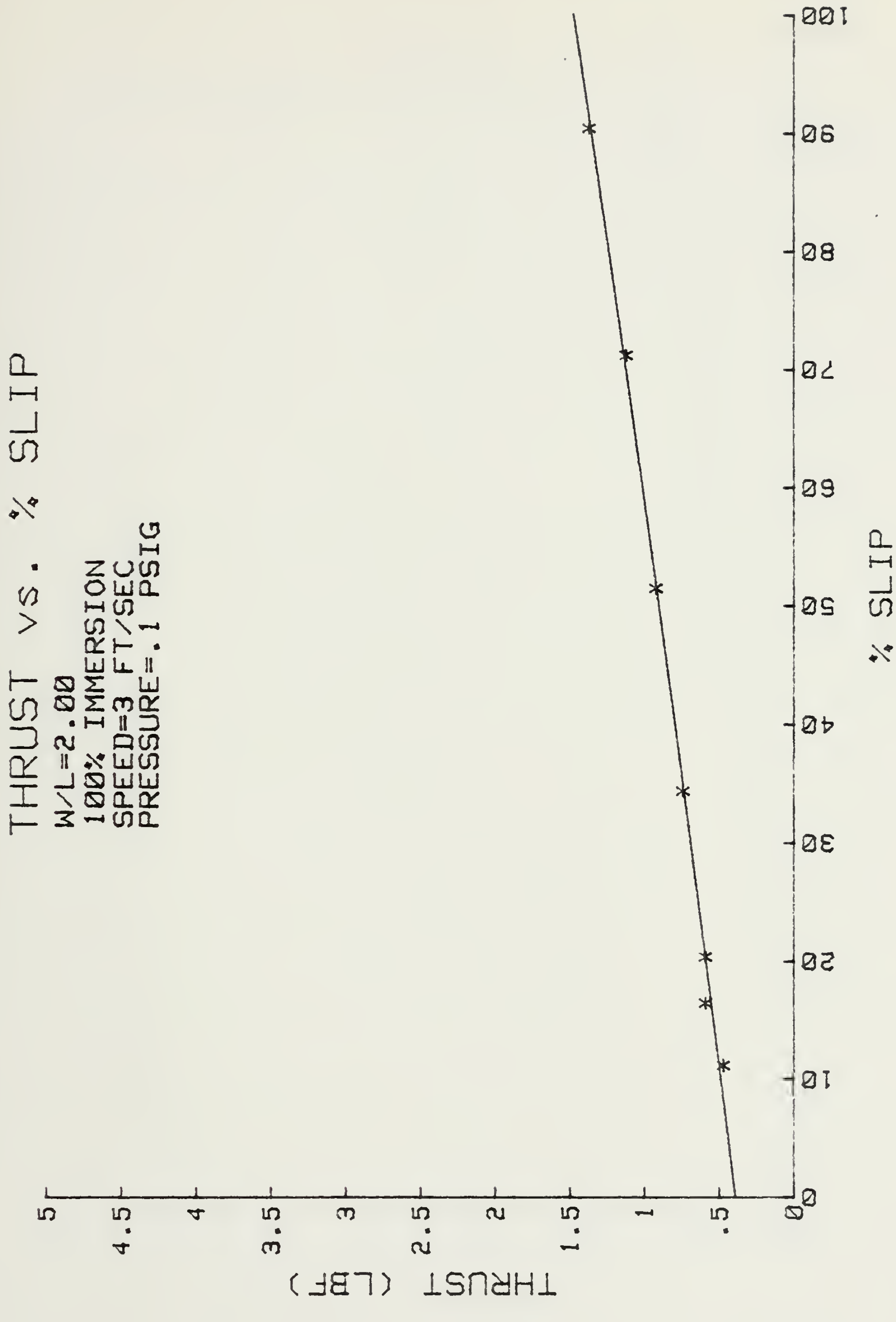


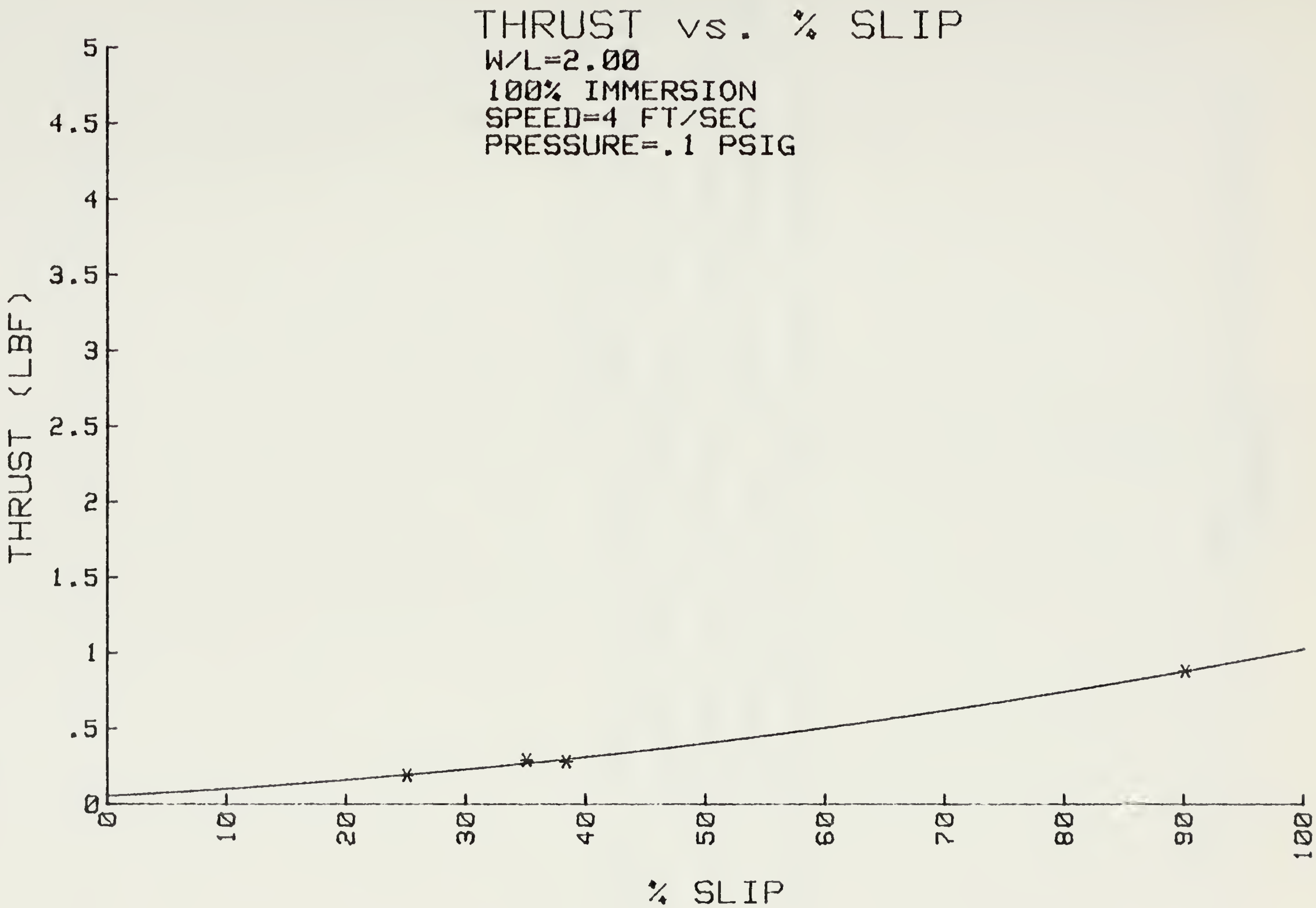
THRUST VS. % SLIP
W/L=2.00
67% IMMERSION
SPEED=3 FT/SEC
PRESSURE=.1 PSIG
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70
80
90
100


THRUST VS. % SLIP
W/L=2.00
67% IMMERSION
SPEED=4 FT/SEC
PRESSURE=.1 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
% SLIP
0
10
20
30
40
50
60
70
80
90
100


THRUST VS. % SLIP
W/L=2.00
100% IMMERSION
SPEED=1 FT/SEC
PRESSURE=.1 PSIG
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70
80
90
100


THRUST VS. % SLIP
W/L=2.00
100% IMMERSION
SPEED=2 FT/SEC
PRESSURE=.1 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
% SLIP
0
10
20
30
40
50
60
70
80
90
100

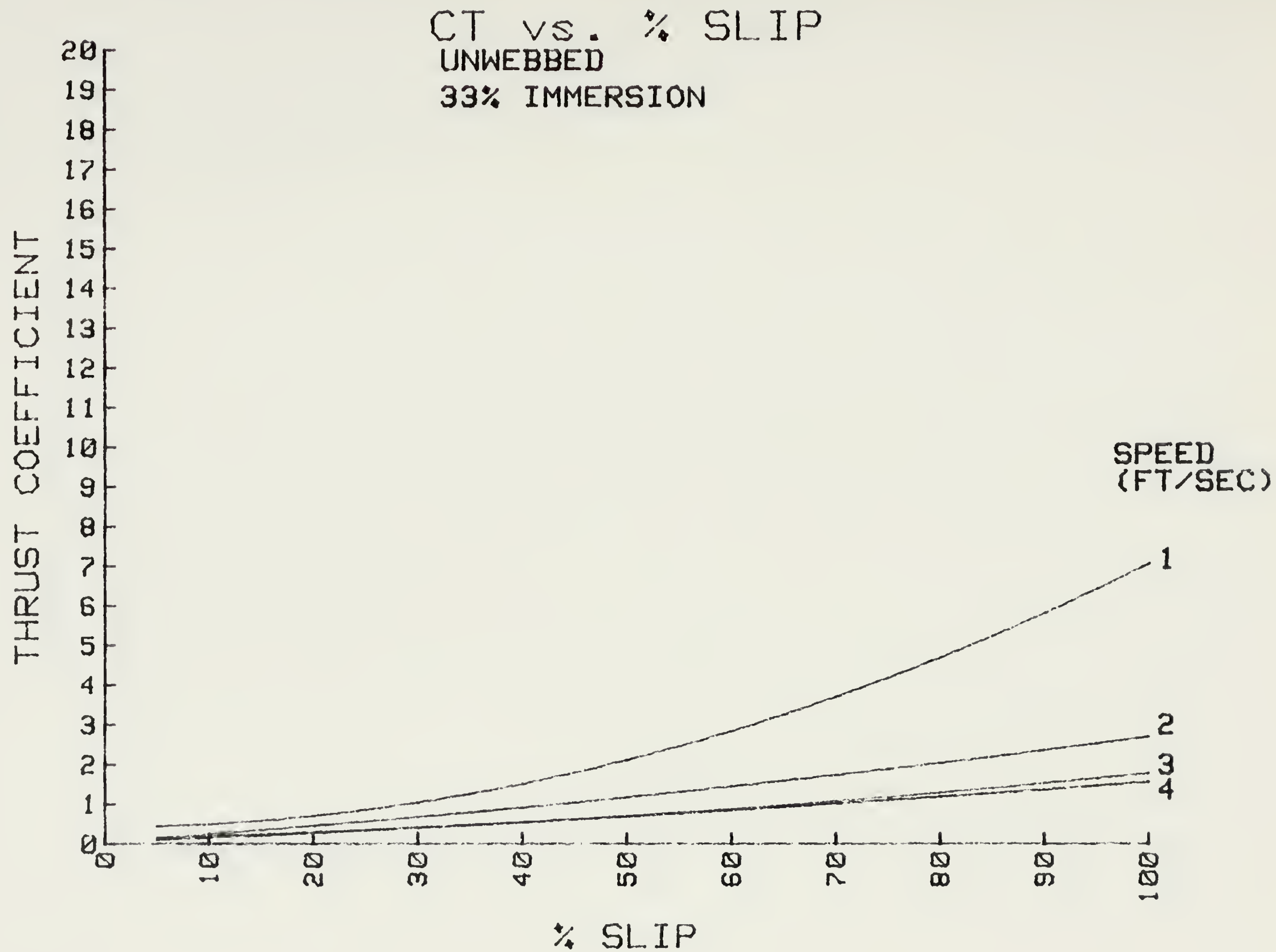

THRUST VS. % SLIP
W/L=2.00
100% IMMERSION
SPEED=3 FT/SEC
PRESSURE=.1 PSIG
THRUST (LBF)
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
% SLIP
0
10
20
30
40
50
60
70
80
90
100

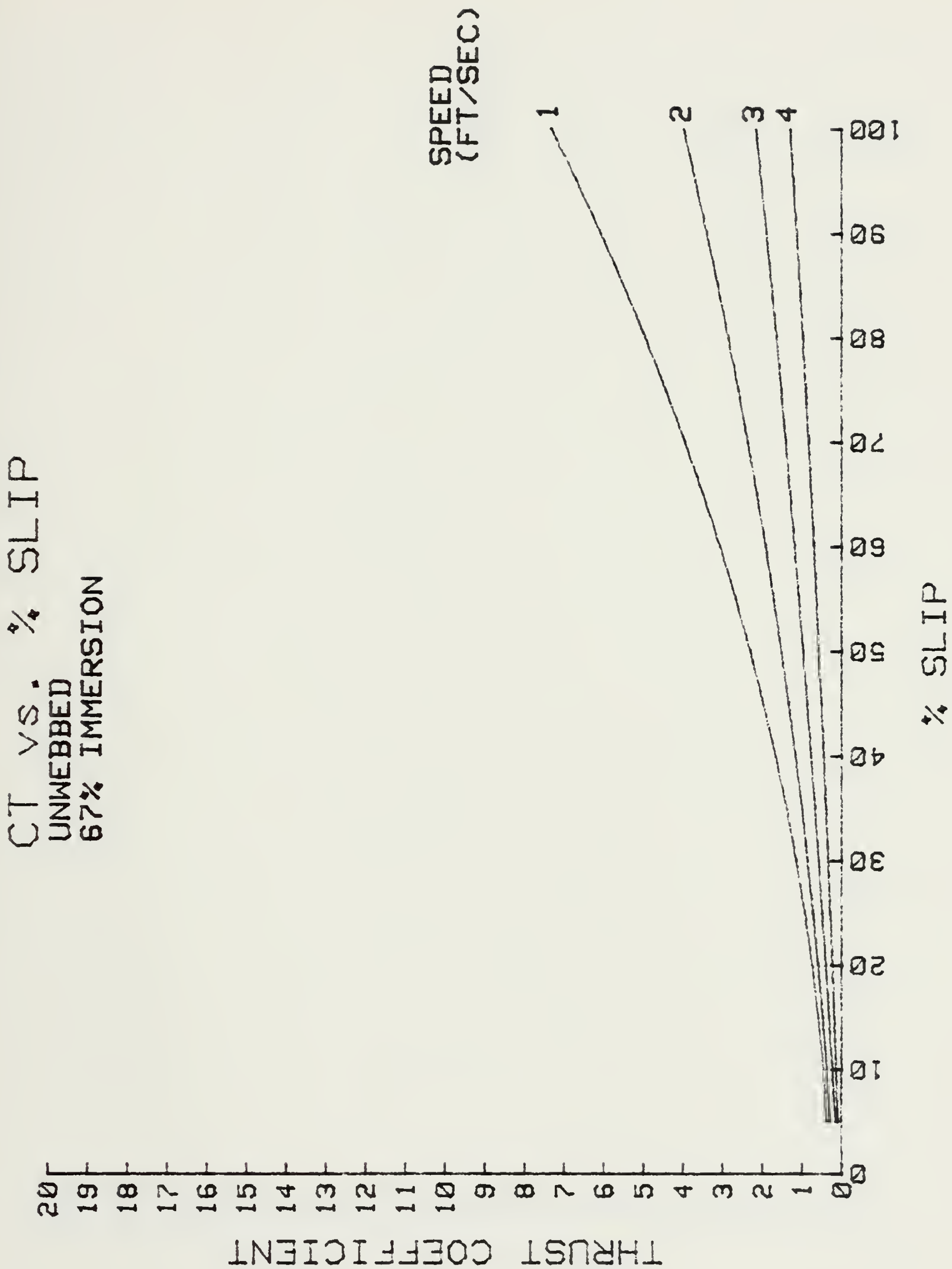

THRUST vs. % SLIP
W/L=2.00
100% IMMERSION
SPEED=4 FT/SEC
PRESSURE=.1 PSIG
THRUST (LBF)
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70
80
90
100

APPENDIX E

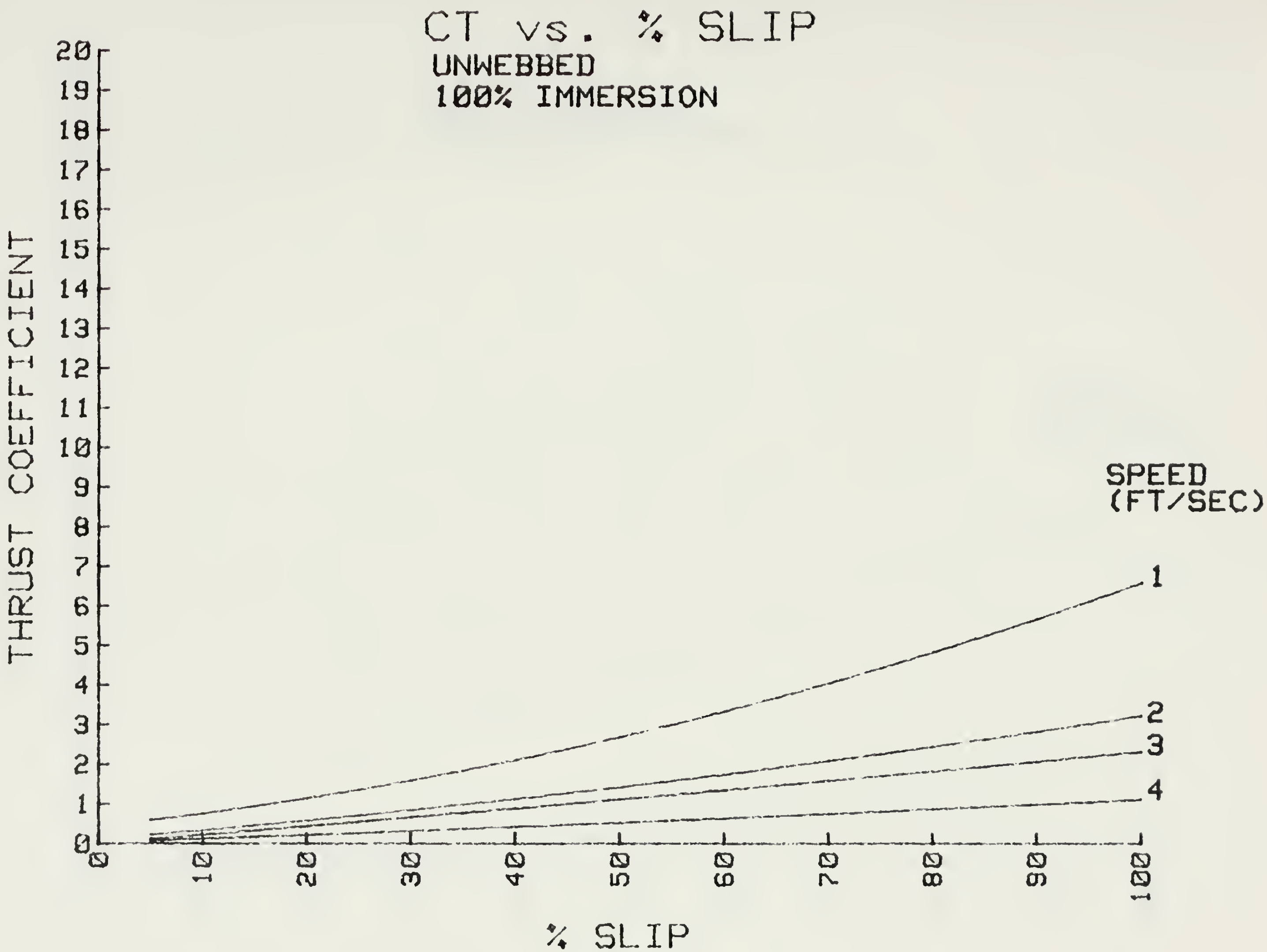
PARAMETER COMPARISONS IN TERMS OF CT VS. % SLIP

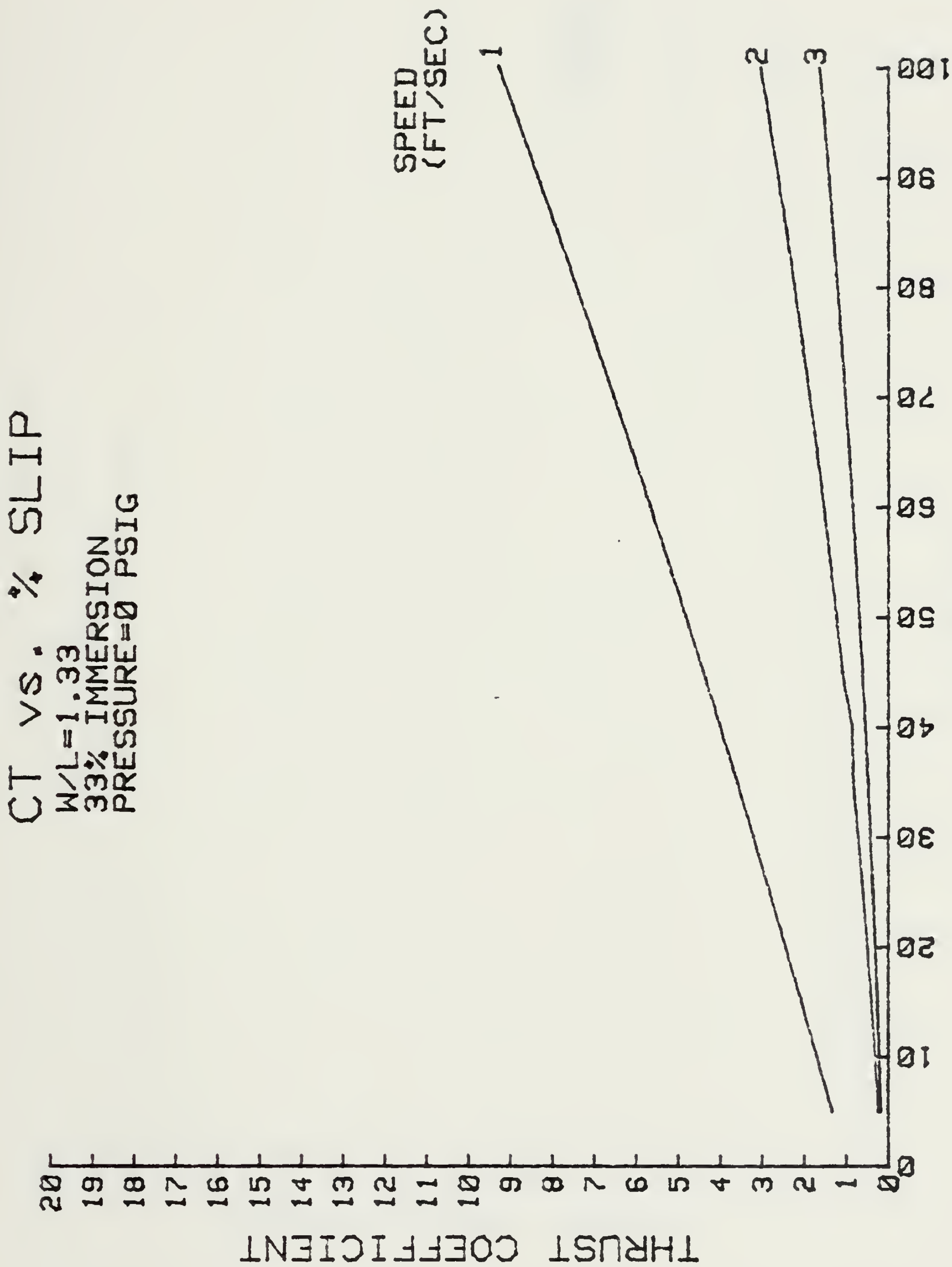
This appendix contains some useful comparisons of system parameter effects on thrust. The data is presented in terms of THRUST COEFFICIENT vs. % SLIP with data gathered from the curve fit solutions of Appendix D. These curves are helpful in ascertaining the specific effects and trends caused by changes in system parameters.

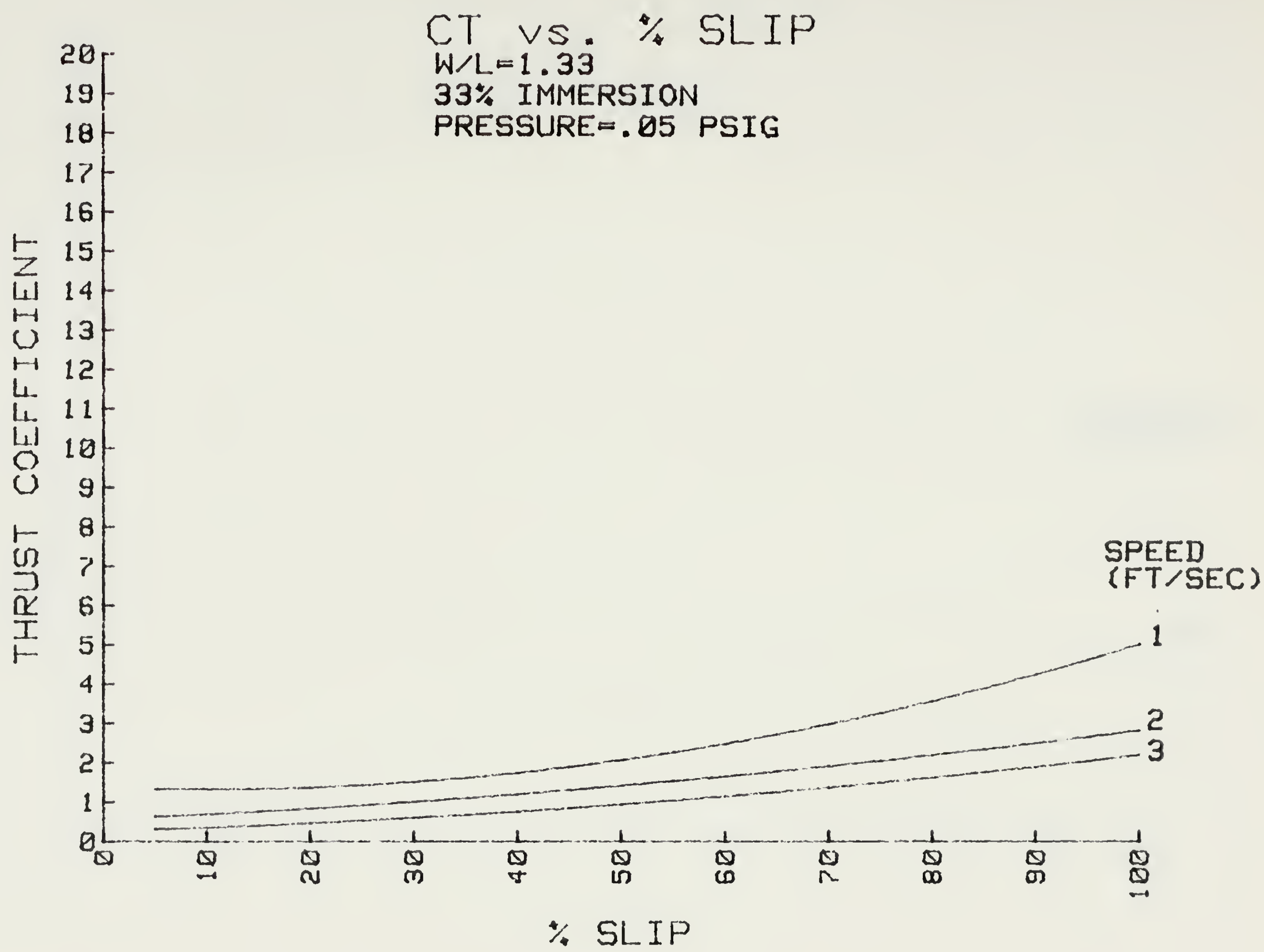

CT vs. % SLIP
UNWEBBED
33% IMMERSION
THRUST COEFFICIENT
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
% SLIP
0
10
20
30
40
50
60
70
80
90
100
SPEED
(FT/SEC)
1
2
3
4

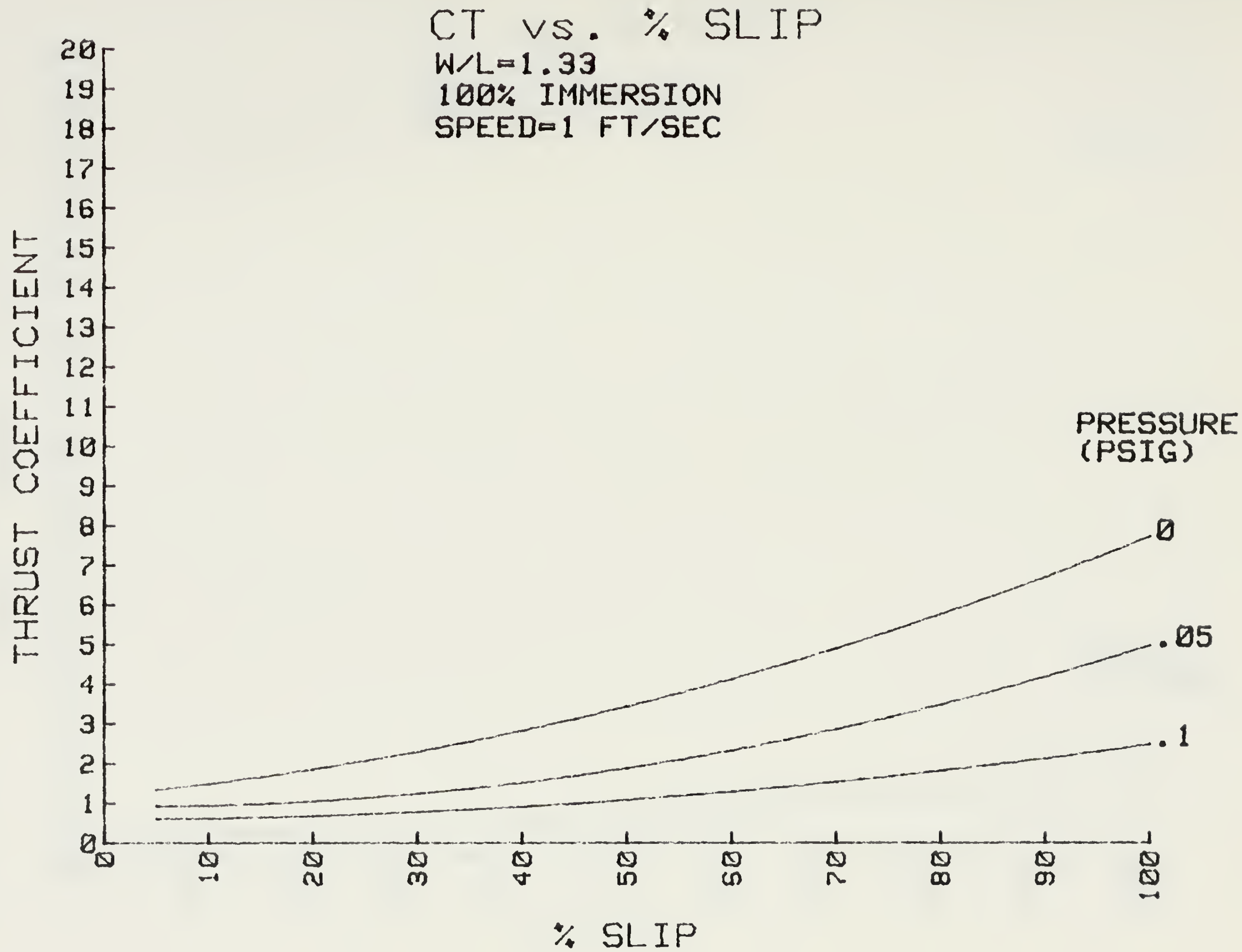


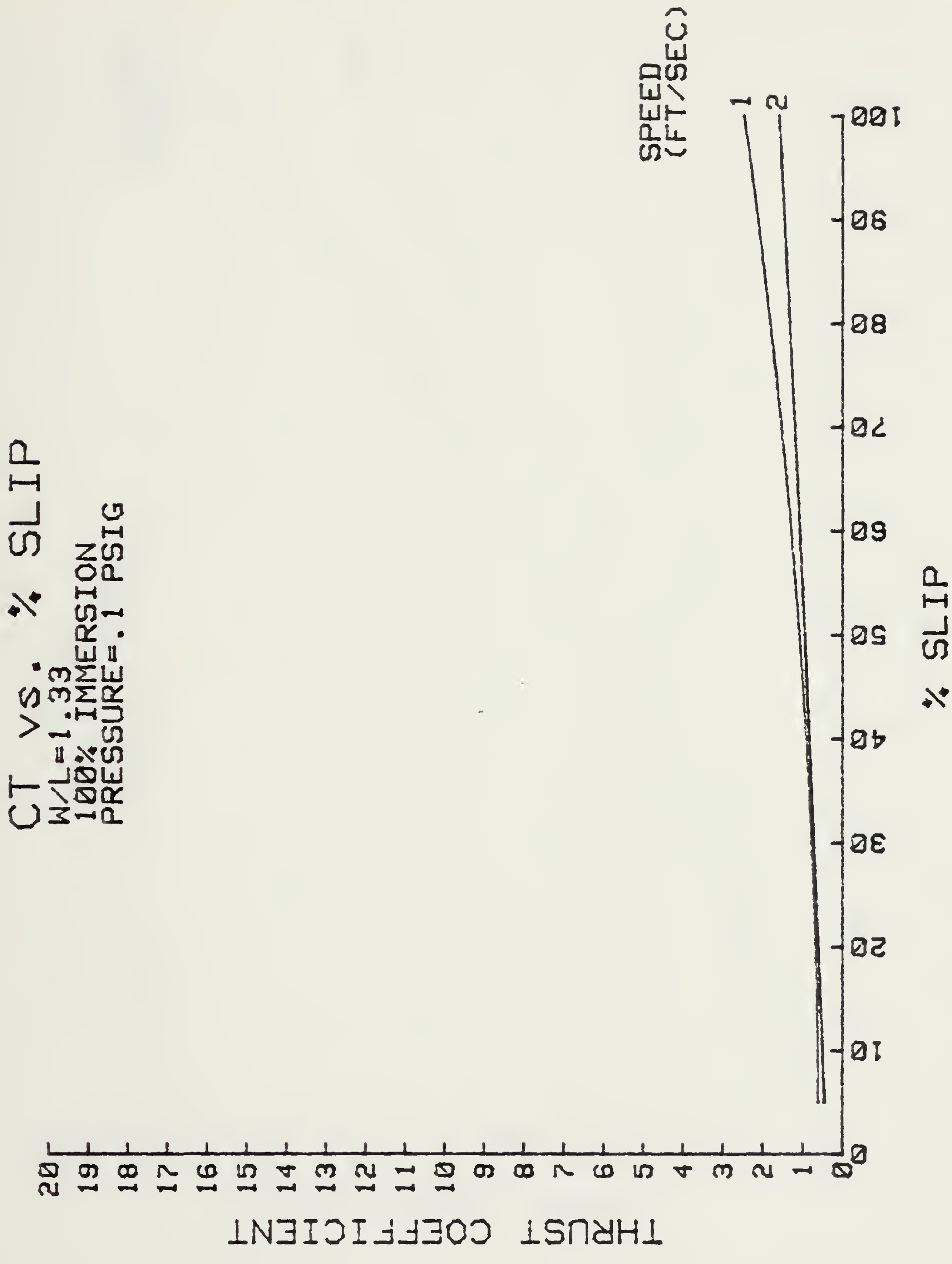
CT VS. % SLIP
UNWEBBED
67% IMMERSION
SPEED
(FT/SEC)
1
2
3
4
THRUST COEFFICIENT
% SLIP
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
0 10 20 30 40 50 60 70 80 90 100

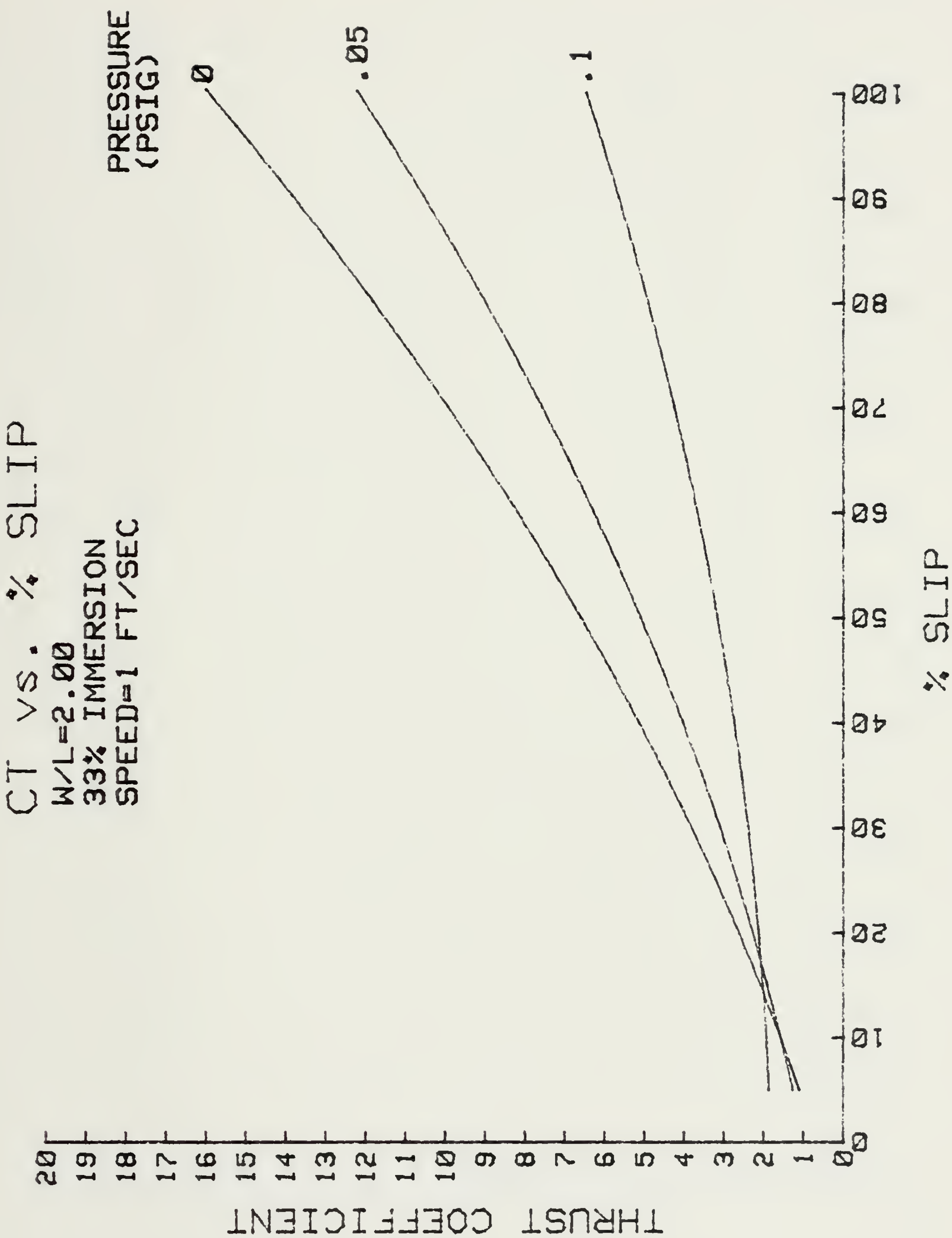

CT vs. % SLIP
UNWEBBED
100% IMMERSION
THRUST COEFFICIENT
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
% SLIP
0
10
20
30
40
50
60
70
80
90
100
SPEED
(FT/SEC)
1
2
3
4

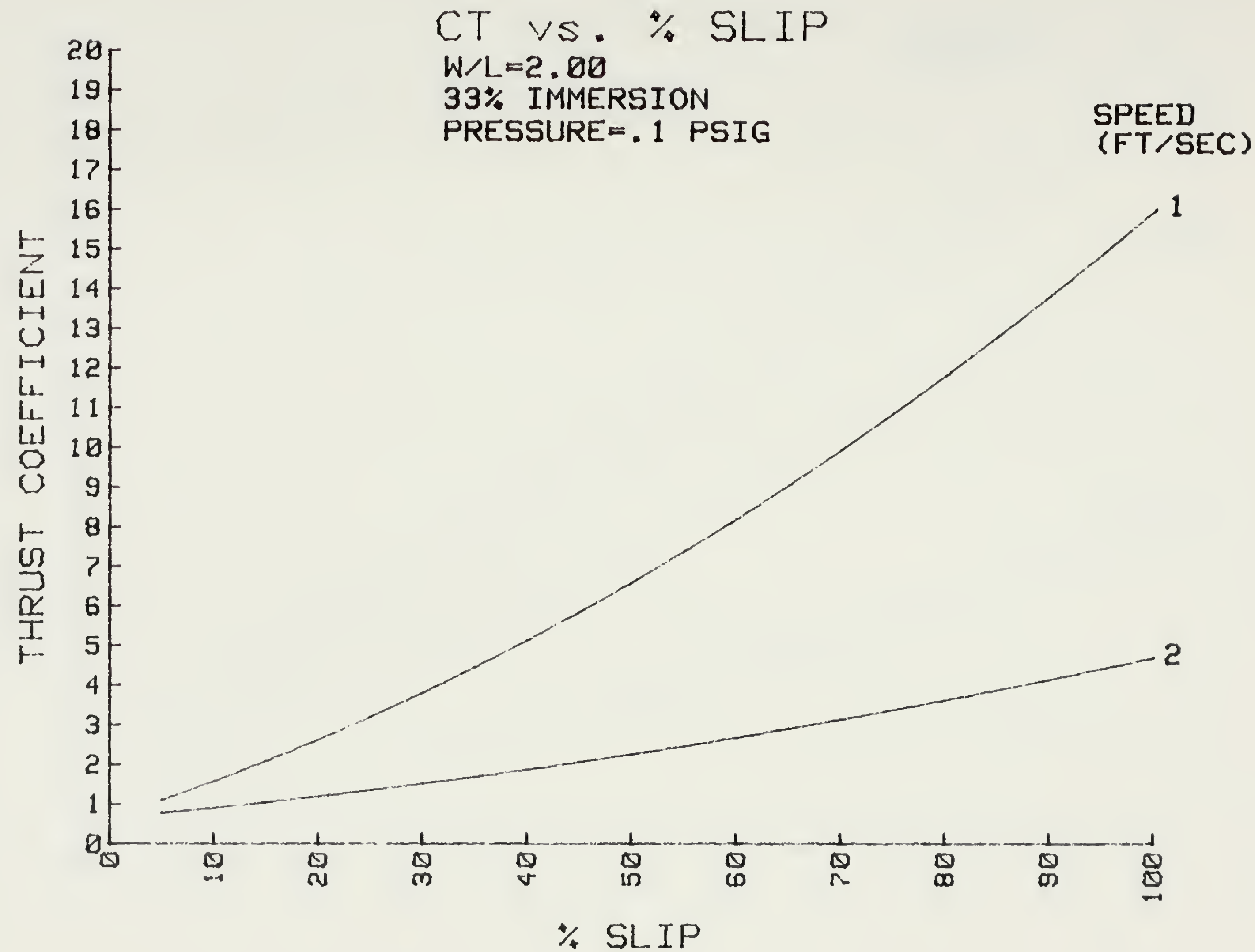

CT VS. % SLIP
W/L=1.33
33% IMMERSION
PRESSURE=0 PSIG
SPEED
(FT/SEC)
1
2
3
THRUST COEFFICIENT
% SLIP
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
10
20
30
40
50
60
70
80
90
100

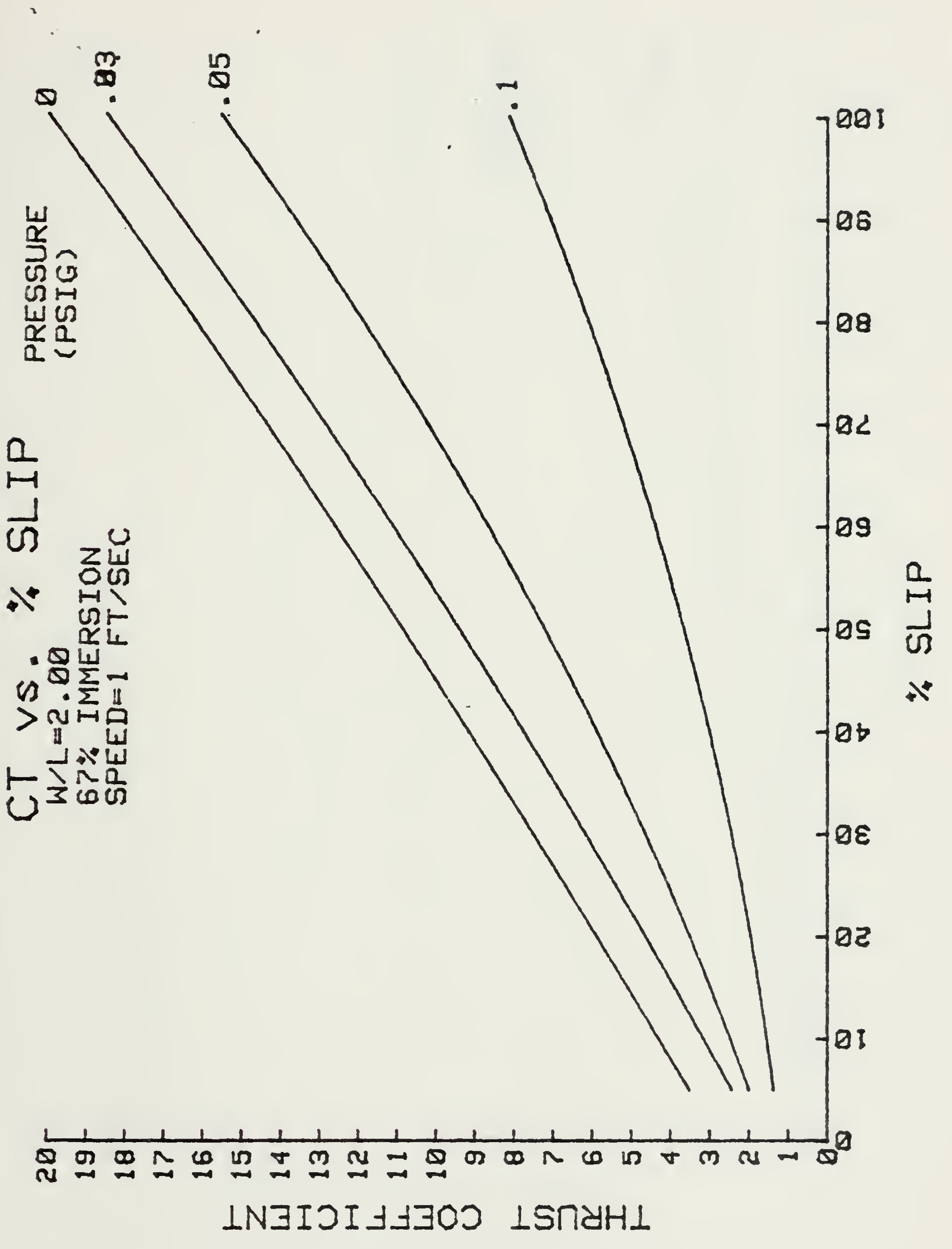

CT vs. % SLIP
W/L=1.33
33% IMMERSION
PRESSURE=.05 PSIG
THRUST COEFFICIENT
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90
100
% SLIP
SPEED
(FT/SEC)
1
2
3


CT vs. % SLIP
W/L=1.33
100% IMMERSION
SPEED=1 FT/SEC
THRUST COEFFICIENT
% SLIP
PRESSURE (PSIG)
0
.05
.1
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20


CT VS. % SLIP
W/L=1.33
100% IMMERSION
PRESSURE=.1 PSIG
SPEED
(FT/SEC)
1
2
THRUST COEFFICIENT
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
% SLIP
0 10 20 30 40 50 60 70 80 90 100


CT VS. % SLIP
W/L=2.00
33% IMMERSION
SPEED=1 FT/SEC
PRESSURE (PSIG)
Ø
.05
.1
THRUST COEFFICIENT
% SLIP
Ø 1 2 3 4 5 6 7 8 9 1Ø 11 12 13 14 15 16 17 18 19 2Ø
Ø 1Ø 2Ø 3Ø 4Ø 5Ø 6Ø 7Ø 8Ø 9Ø 1ØØ


CT vs. % SLIP
W/L=2.00
33% IMMERSION
PRESSURE=.1 PSIG
SPEED
(FT/SEC)
1
2
THRUST COEFFICIENT
% SLIP
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
10
20
30
40
50
60
70
80
90
100


CT VS. % SLIP
W/L=2.00
67% IMMERSION
SPEED=1 FT/SEC
PRESSURE
(PSIG)
0
.03
.05
.1
THRUST COEFFICIENT
% SLIP
0
1
2
3
4
5
6
7
8
9
10
11
12
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14
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16
17
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20
10
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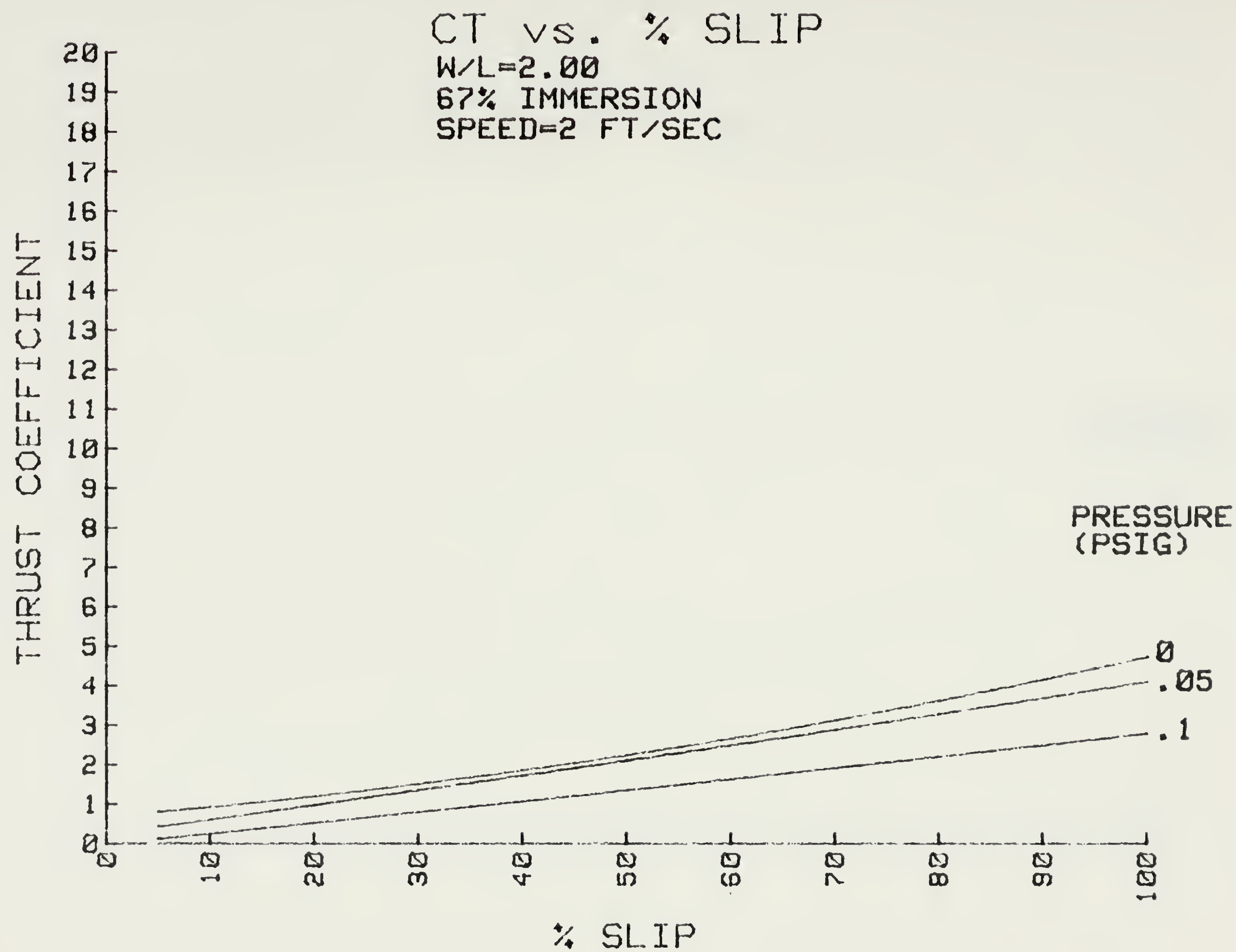
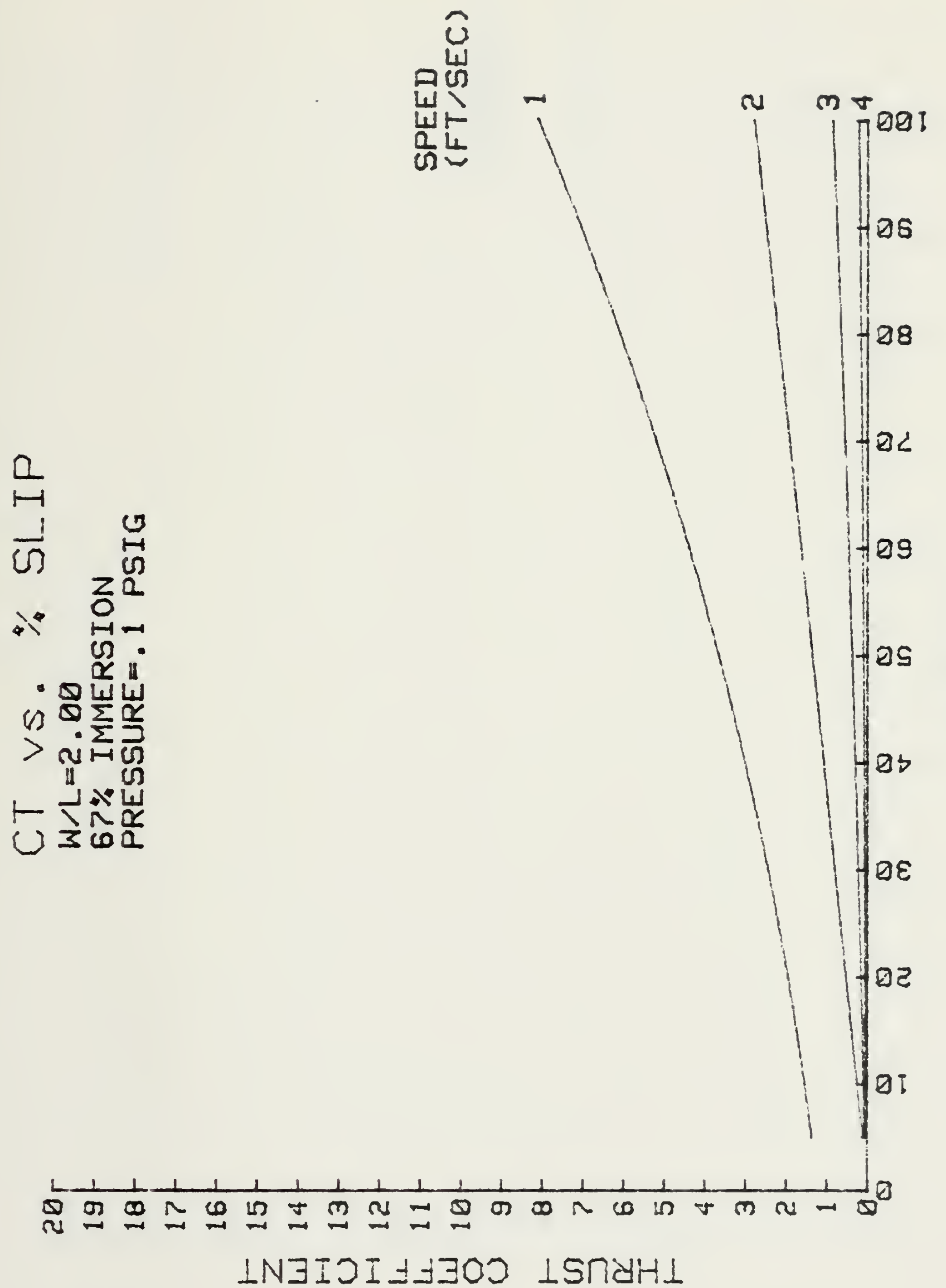
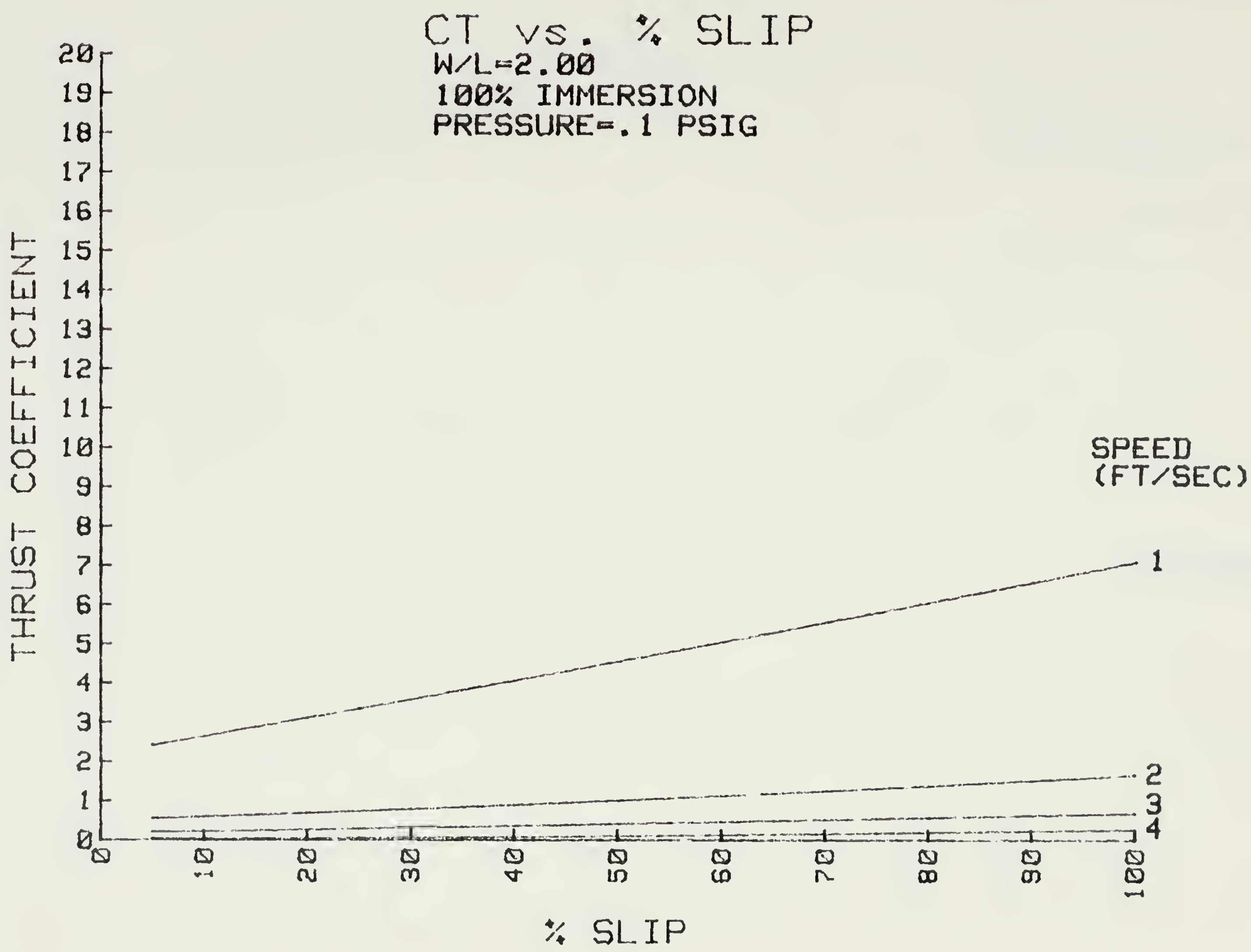
30
40
50
60
70
80
90
100



CT vs. % SLIP
W/L=2.00
67% IMMERSION
SPEED=2 FT/SEC
THRUST COEFFICIENT
% SLIP
PRESSURE (PSIG)
0
.05
.1



CT VS. % SLIP
W/L=2.00
67% IMMERSION
PRESSURE=.1 PSIG
SPEED (FT/SEC)
1
2
3
4
THRUST COEFFICIENT
% SLIP
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
0 10 20 30 40 50 60 70 80 90 100



CT vs. % SLIP
W/L=2.00
100% IMMERSION
PRESSURE=.1 PSIG
THRUST COEFFICIENT
0
1
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7
8
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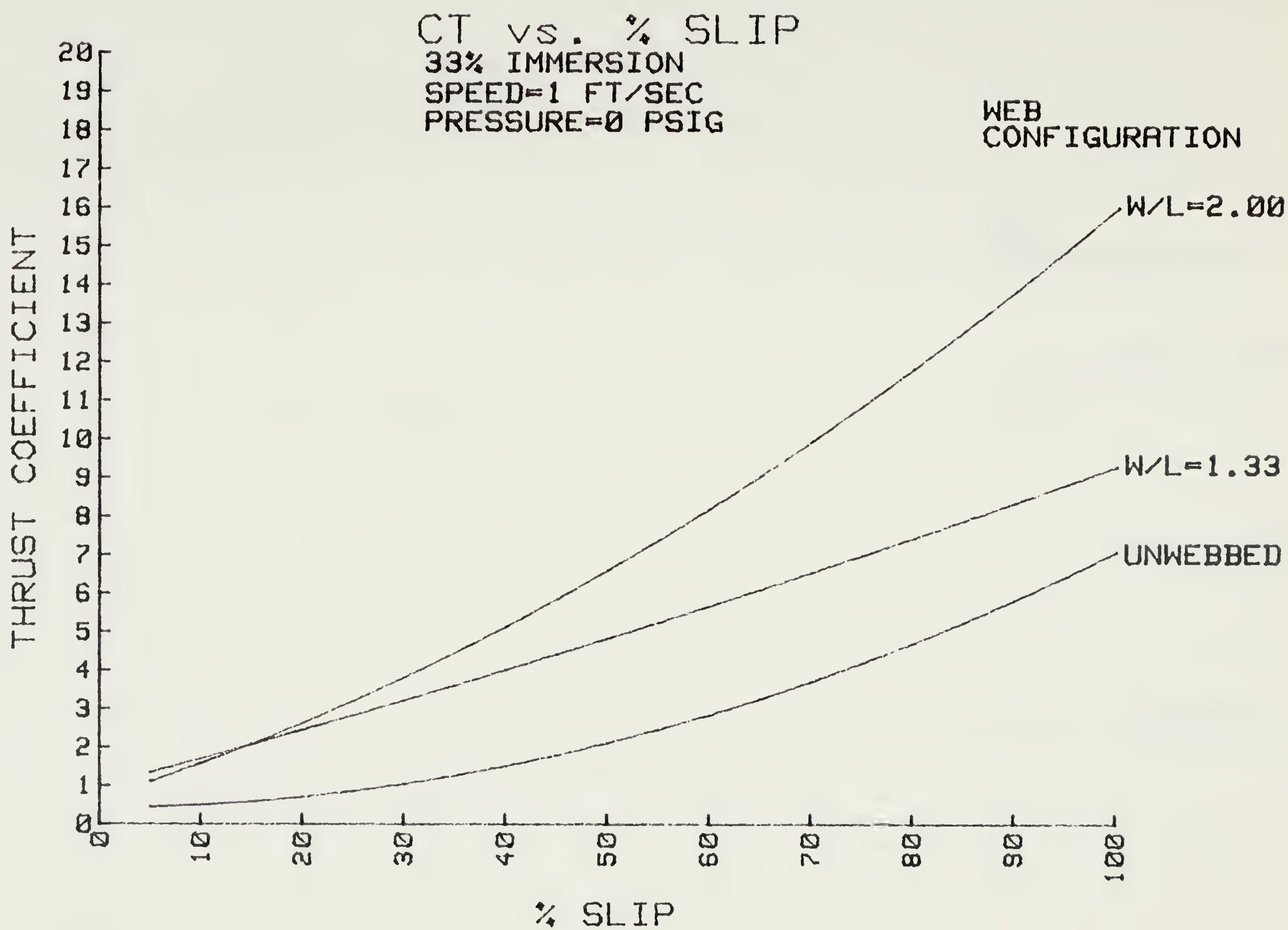
10
11
12
13
14
15
16
17
18
19
20
% SLIP
0
10
20
30
40
50
60
70
80
90
100
SPEED
(FT/SEC)
1
2
3
4


CT vs. % SLIP
33% IMMERSION
SPEED=1 FT/SEC
PRESSURE=0 PSIG
WEB
CONFIGURATION
W/L=2.00
W/L=1.33
UNWEBBED
THRUST COEFFICIENT
% SLIP
0
1
2
3
4
5
6
7
8
9
10
11
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0
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40
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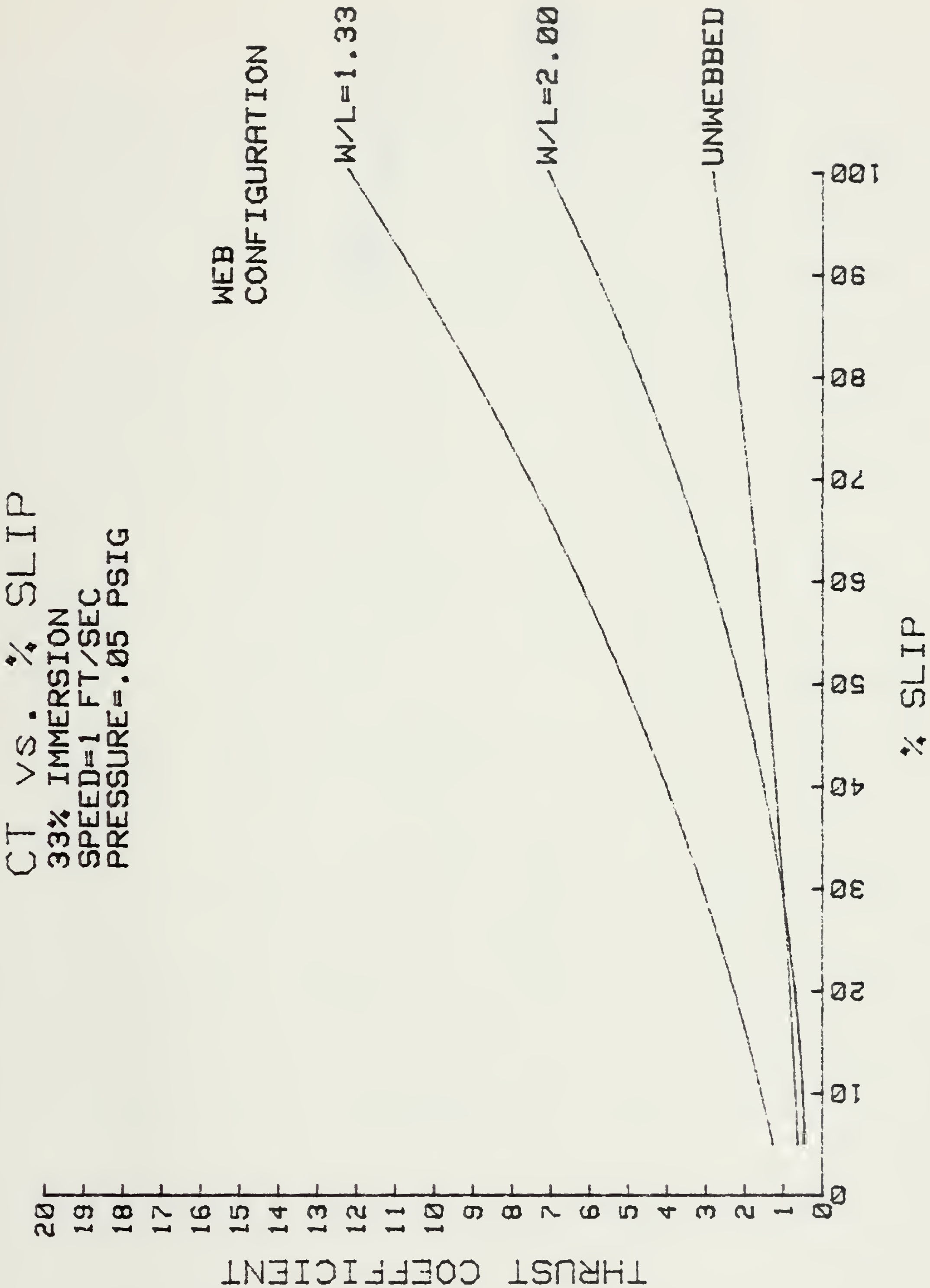
100


CT VS. % SLIP
33% IMMERSION
SPEED=1 FT/SEC
PRESSURE=.05 PSIG
WEB
CONFIGURATION
W/L=1.33
W/L=2.00
UNWEBBED
THRUST COEFFICIENT
% SLIP
0
1
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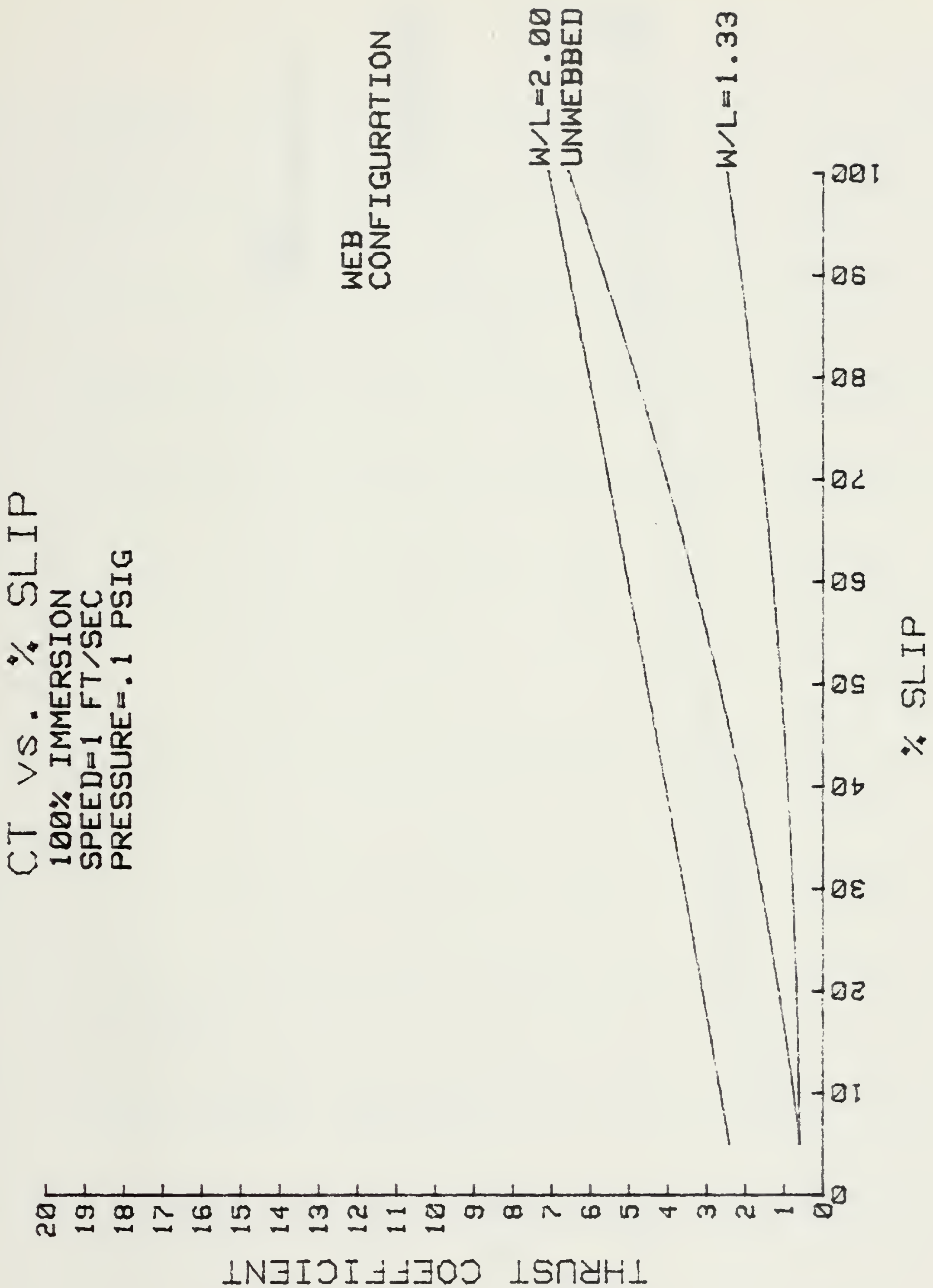

CT VS. % SLIP
100% IMMERSION
SPEED=1 FT/SEC
PRESSURE=.1 PSIG
WEB
CONFIGURATION
W/L=2.00
UNWEBBED
W/L=1.33
THRUST COEFFICIENT
% SLIP
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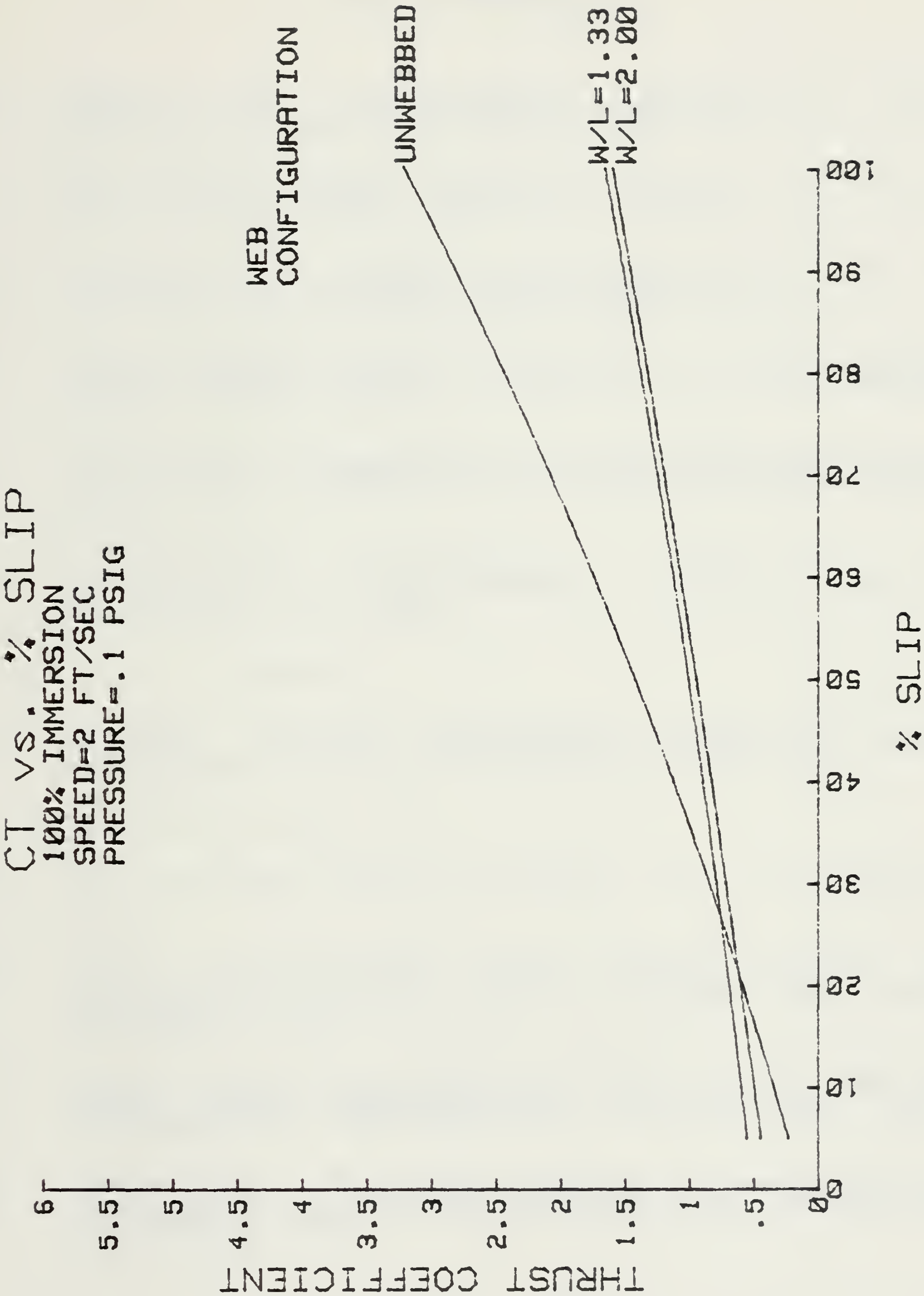
CT VS. % SLIP
100% IMMERSION
SPEED=2 FT/SEC
PRESSURE=.1 PSIG
WEB
CONFIGURATION
UNWEBBED
W/L=1.33
W/L=2.00
THRUST COEFFICIENT
% SLIP
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
10
20
30
40
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60
70
80
90
100

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